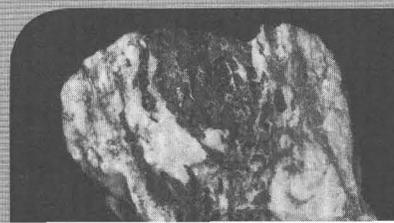
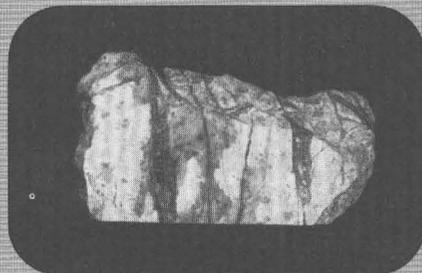
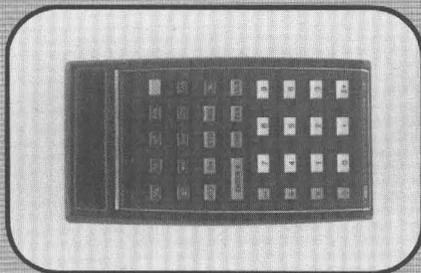
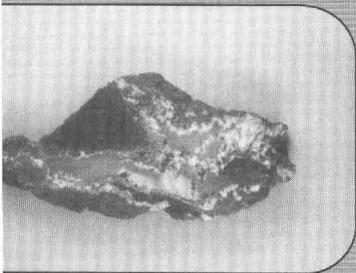
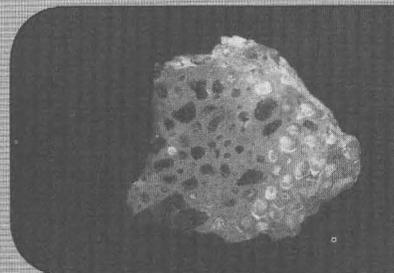
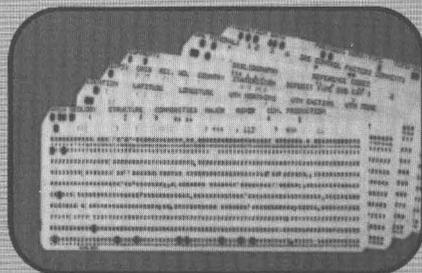
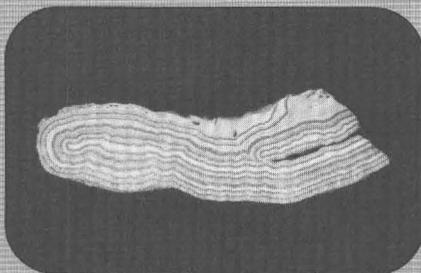
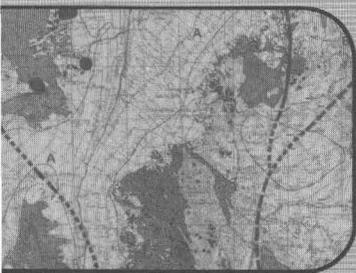
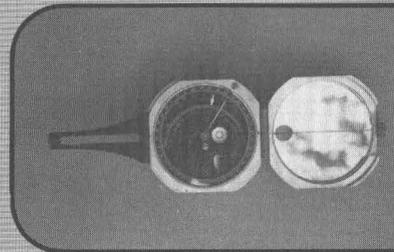
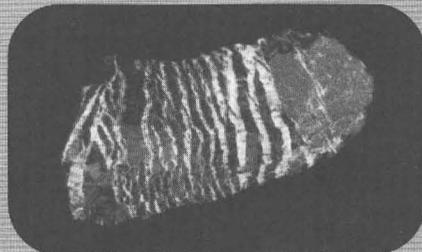
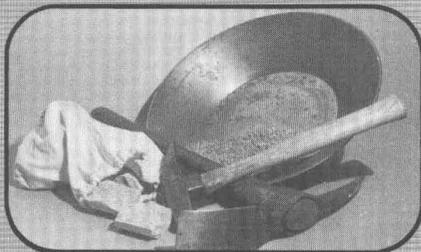
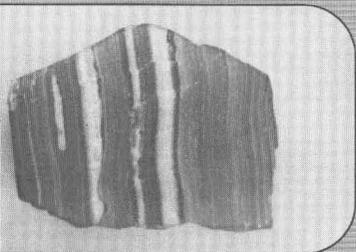
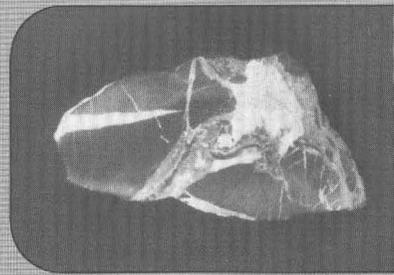
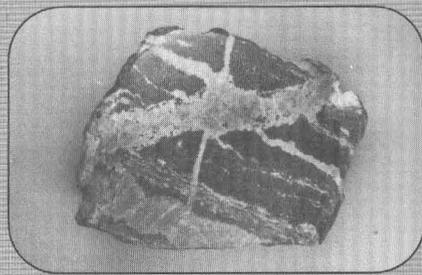
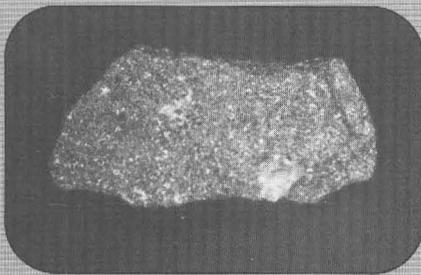
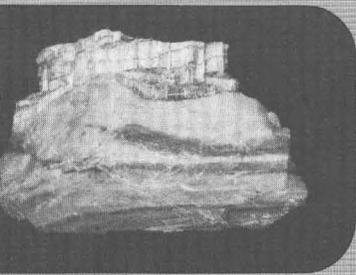


Geology and Resources of Fluorine in the United States

GEOLOGICAL SURVEY PROFESSIONAL PAPER 933



COVER PHOTOGRAPHS

1	2	3	4
5		6	
	7		8
9		10	
11	12	13	14

1. Asbestos ore
2. Lead ore, Balmat mine, N. Y.
3. Chromite-chromium ore, Washington
4. Zinc ore, Friedensville, Pa.
5. Banded iron-formation, Palmer, Mich.
6. Ribbon asbestos ore, Quebec, Canada
7. Manganese ore, banded rhodochrosite
8. Aluminum ore, bauxite, Georgia
9. Native copper ore, Keweenaw Peninsula, Mich.
10. Porphyry molybdenum ore, Colorado
11. Zinc ore, Edwards, N. Y.
12. Manganese nodules, ocean floor
13. Botryoidal fluorite ore, Poncha Springs, Colo.
14. Tungsten ore, North Carolina

Geology and Resources of Fluorine in the United States

Edited by DANIEL R. SHAWE

With sections by D. R. SHAWE, R. E. VAN ALSTINE,
R. G. WORL, A. V. HEYL, R. D. TRACE, R. L. PARKER,
W. R. GRIFFITTS, C. L. SAINSBURY, and J. B. CATHCART

GEOLOGICAL SURVEY PROFESSIONAL PAPER 933

*An evaluation of the geochemistry,
geographic distribution, and
geologic environments of fluorine,
and descriptions of major United
States fluorine mineral deposits*



UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 76-600061

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02901-4

APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimates include currently minable resources (*reserves*) as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once they are discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the Earth's crust, depends greatly on geologic availability and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of fluorine as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

Professional Paper 820—"United States Mineral Resources"

Professional Paper 907—"Geology and Resources of Copper Deposits"

Professional Paper 926—"Geology and Resources of Vanadium Deposits"

Professional Paper 959—"Geology and Resources of Titanium in the United States"

CONTENTS

	Page		Page
Abstract	1	Descriptions of major fluorine deposits and districts and important types of fluorine occurrences—Continued	
Introduction, by R. E. Van Alstine.....	3	Colorado-New Mexico-western Texas-southeastern	
Geochemistry of fluorine, by D. R. Shawe	4	Arizona, by R. G. Worl, W. R. Griffiths, and R. E. Van Alstine	48
Abundance of fluorine in rocks	5	Descriptions of individual districts and deposits	53
Abundance of fluorine in gases and waters	9	Colorado	53
Geochemical cycle of fluorine.....	12	Jamestown.....	53
Element associations, by R. E. Van Alstine and D. R. Shawe.....	14	Northgate	56
Geographic distribution of fluorine in igneous rocks, by D. R. Shawe	15	Other deposits	58
Geologic environments and distribution of fluorine, by D. R. Shawe and R. E. Van Alstine	17	New Mexico.....	59
Fluorine in fluorite deposits and occurrences	17	Burro Mountains.....	59
Fluorine in topaz deposits and occurrences.....	19	Gila.....	59
Fluorine in phosphate and fluorapatite deposits	19	Cooks Peak-Fluorite Ridge.....	59
Fluorine in other deposits.....	19	Sierra Cuchillo.....	60
Tectonic setting of fluorine deposits, by D. R. Shawe.....	22	Zuni Mountains	61
Relation of fluorine deposits to faults.....	22	Sierra Caballos	61
Relation of fluorine deposits to intrusive igneous rocks	25	Grants.....	61
Relation of fluorine deposits to geophysical properties.....	27	Southeastern Arizona	62
Descriptions of major fluorine deposits and districts and important types of fluorine occurrences.....	30	Duncan	62
Alaska, by C. L. Sainsbury.....	30	Other deposits	62
Descriptions of individual districts and deposits	30	Central and Eastern United States, by A. V. Heyl and R. E. Van Alstine	62
Lost River.....	30	Illinois-Kentucky.....	63
Other deposits	33	Illinois-Kentucky fluorspar district, by R. D. Trace	63
Washington-Idaho-Montana-Wyoming-South Dakota, by R. L. Parker.....	34	Geologic setting	65
Descriptions of individual districts and deposits	34	Fluorspar ore deposits.....	70
Washington	34	Summary	72
Idaho.....	35	Central Kentucky.....	74
Meyers Cove	35	Cumberland River, Kentucky	74
Bayhorse	36	Tennessee-North Carolina-Virginia.....	74
Stanley area	36	Central Tennessee.....	74
Big Squaw Creek.....	37	Sweetwater, Tennessee	75
Other deposits.....	37	Del Rio, Tennessee-Hot Springs, North Carolina	75
Montana	38	Hamme, North Carolina-Virginia.....	76
Crystal Mountain.....	38	Faber, Virginia	76
Snowbird.....	38	Other deposits, Virginia.....	76
Spar	39	Alabama.....	77
Other deposits	39	Missouri-Arkansas-central Texas	77
Wyoming.....	40	Southeast Missouri	77
South Dakota.....	41	Other deposits, Missouri and Arkansas	77
Nevada-western Utah-southeastern Oregon-southeastern California-western Arizona, by R. G. Worl and W. R. Griffiths.....	41	Llano uplift, central Texas.....	77
Descriptions of individual districts and deposits.....	43	New York.....	78
Nevada	43	Adirondack Mountains	78
Broken Hills.....	43	Other deposits	78
Quinn Canyon Range.....	44	New England.....	79
Utah.....	47	Cheshire County-Westmoreland, New Hampshire	79
Spor Mountain.....	47	North Chatham, New Hampshire	79
Arizona	47	Long Hill (Trumbull)-Monroe, Connecticut.....	79
Castle Dome	47	Long Island, Blue Hill Bay, Maine.....	79
Other deposits	48	Other districts and deposits of the Central and Eastern United States.....	79
		Fluorine in phosphate deposits, by J. B. Cathcart.....	82

	Page		Page
Present and future resources of fluorine, by D. R. Shawe, R. G. Worl, R. E. Van Alstine, and A. V. Heyl.....	83	Present and future resources of fluorine—Continued	
Summary of fluorine resources, by R. E. Van Alstine and R. G. Worl.....	83	Suggestions for likely future fluorine provinces: Speculative fluorine resources, by D. R. Shawe, R. G. Worl, and A. V. Heyl	86
Known favorable areas for fluorine exploration, by D. R. Shawe, R. E. Van Alstine, R. G. Worl, and A. V. Heyl.....	85	Geochemical and geophysical prospecting methods for fluorine, by W. R. Griffiths and R. E. Van Alstine.....	89
		References.....	91

ILLUSTRATIONS

FIGURES		Page
1–5. Graphs:		
1. Fluorine and silica contents of olivine basalt from Kilauea, Hawaii		6
2. Fluorine and silica contents of five igneous suites		6
3. Fluorine and silica contents of nine igneous suites from the United States.....		7
4. Fluorine and silica contents of basalts and andesites from Western United States and Antarctica		8
5. Fluorine and silica contents of hybrid granitoid rocks of Jurassic age and aplite of Oligocene age from the southern Snake Range, Nevada.....		9
6. Map showing distribution of fluoride content of ground water in the United states.....		11
7. Scatter diagram showing relation of fluorine to silica in volcanic rocks.....		13
8–17. Maps:		
8. Distribution of fluorine-rich igneous rocks in the United States.....		16
9. Distribution of fluorite deposits in the United States.....		18
10. Locations of major topaz deposits, topaz occurrences, and topaz-bearing rhyolites in the United States.....		20
11. Locations of phosphate and fluorapatite deposits in the United States		21
12. Major faults, distribution of fluorine minerals, and major belts of fluorite deposits in the United States.....		23
13. Normal faults, and distribution of fluorine mineral deposits in the Western United States		24
14. Major Phanerozoic intrusive bodies and distribution of fluorine minerals in the United States		26
15. Bouguer gravity map and distribution of fluorine mineral deposits in the United States.....		28
16. Fluorite mineral belts and high heat-flow regions in the Western United States and positive aeromagnetic anomalies in Colorado.....		29
17. Crustal thickness, crustal seismic velocity, upper-mantle seismic velocity, and distribution of fluorine mineral deposits in the United States		31
18. Longitudinal projection along "main vein" of the Baxter (Kaiser) fluorspar mine, Broken Hills district , Nevada.....		44
19–21. Maps:		
19. Locations of fluorspar deposits in the Quinn Canyon Range, Nev.....		45
20. Jamestown district, Colorado		54
21. Fluorspar deposit at the Burlington mine, Jamestown district, Colorado.....		55
22. Sketch showing slab of fluorspar from Northgate, Colo		58
23. Map showing major structural features, igneous rocks, and distribution of known fluorspar deposits, Illinois- Kentucky fluorspar district.....		64
24. Stratigraphic column, Illinois-Kentucky fluorspar district.....		66
25. Generalized stratigraphic column, western Kentucky fluorspar district.....		67
26. Map showing major structural features in the region surrounding the Illinois-Kentucky fluorspar district		69
27. Cross section of Davenport mine, Moore Hill area, Kentucky.....		70
28. Map of Cave in Rock fluorspar district, Hardin County, Ill.....		71

GEOLOGY AND RESOURCES OF FLUORINE IN THE UNITED STATES

Edited by D. R. SHAW

ABSTRACT

Fluorine mineral resources are evaluated in this report in the perspective of the geochemistry of fluorine and the geologic environment of fluorine mineral deposits. Rapidly increasing demand and the possibility of shortages in supply of fluorspar and other fluorine products that are vital to the economy of the United States prompted this review of fluorine resources.

Continental crustal abundance of fluorine averages about 650 ppm (parts per million); basalts and gabbros average about 400–500 ppm, andesites and granodiorites 600 ppm, and rhyolites and granites 800 ppm; alkalic extrusive and intrusive rocks average much higher, 900–2,600 ppm. Despite the higher *average* fluorine content of silicic rocks, many silicic rocks contain as little fluorine as do low-fluorine mafic rocks. Intrusive rocks tend to contain higher amounts of fluorine than do extrusive rocks of similar composition. Metamorphic and sedimentary rocks have average fluorine contents similar to those of igneous rocks. Sandstones, carbonate rocks, and evaporites average about 200–250 ppm F, and oceanic sediments and shales 700–900 ppm. Marine phosphorites contain remarkably more fluorine, averaging more than 30,000 ppm. Soils average less than 300 ppm F.

In some comagmatic series of igneous rocks, fluorine increases with silica, and has been concentrated by magmatic differentiation. In other series fluorine decreases with silica, and the fluorine distribution in the rocks appears to have resulted from wallrock contamination. A further control of the abundance of fluorine in igneous rocks is the presence or absence of minerals that can readily accommodate fluorine in their crystal structures, so that hornblende- and biotite-rich rocks may contain more fluorine than do more silicic members of the same igneous series.

Fluorine content is lowest in igneous rocks that have been irrupted through oceanic crust and highest in igneous rocks irrupted through continental crust. Fluorine appears to be highest in rocks of alkalic affinity and these appear to have originated mainly as magmas derived from the mantle beneath the continental crust.

Some volcanic gases and sublimates contain notable amounts of fluorine; in general high-fluorine silicic and alkalic magmas exhale higher amounts of fluorine than do low-fluorine mafic magmas. Expulsion of fluorine from high-fluorine magmas may have occurred principally because of pressure drop due to magma rise.

Surface waters average 0.25 ppm F, and higher contents are found mostly in arid regions. Ground waters contain an average of 0.4 ppm F. Pacific and Atlantic sea waters contain about 1.2 ppm F. Connate and related waters average 2.7 ppm F, and thermal waters associated with volcanoes and epithermal mineral deposits average 5.4 ppm F.

Most of the fluorine transported to the sea is carried in minerals held in suspension and deposited in detrital sedimentary rocks. Only rarely do conditions develop where fluorine is deposited chemically in marine phosphorite deposits.

Fluorine shows a strong geochemical affinity for the assemblage of elements beryllium-lithium-manganese-niobium-tin-tungsten-uranium-yttrium-lead-zinc and is commonly found with these elements in a wide variety of geologic environments.

High-fluorine igneous rocks are geographically restricted to two major provinces in the United States, one a broad belt extending from southern Maine southwestward into Alabama and the other a U-shaped region extending from southwestern Montana southward into southern California, eastward to southwestern New Mexico, and northward through western Colorado. Fluorine-rich igneous rocks in the Eastern United States are dominantly Paleozoic in age and those in the Western United States are dominantly Tertiary in age.

Fluorine mineral deposits occur in a wide variety of geologic environments and in a multitude of forms. Veins, mantos, pipelike bodies, breccia stockworks, contact zones, pegmatites, greisens, disseminated deposits, and bedded layers occur variously associated with or enclosed within volcanic rocks, intrusive igneous rocks, metamorphic rocks, or sedimentary rocks. Fluorite is the most common and abundant fluorine mineral, and fluorspar constitutes the ore of fluorite. Other significant fluorine minerals that likely constitute future resources are topaz, fluorapatite, and the carbonate-apatite of sedimentary phosphate rock. Additional minerals that may become economically significant sources of fluorine are cryolite, sellaite, villiaumite, bastnaesite, and the humite group of silicates.

Fluorine occurs in epigenetic mineral deposits principally in broad provinces in the Eastern and Western United States that coincide closely with the broad provinces of fluorine-rich igneous rocks. On the basis of available age data the deposits also are similar in age to associated igneous rocks. Fluorine is found in marine phosphate rocks chiefly in the Southeastern and the Western United States.

Distribution of epigenetic fluorine mineral deposits in the United States has been strongly controlled by tectonic environment. There is a close spatial association of fluorine mineral deposits with major fault zones. In the Western United States the distribution of Tertiary fluorine mineral deposits closely follows the distribution of Basin-Range structure; some deposits occur in tensional faults. The distribution of fluorine mineral deposits in northwesterly, northeasterly, and easterly belts suggests an association with deep-seated strike-slip fault zones of these orientations that seem to constitute a fundamental structural framework of the continental crust.

Regions of low gravity in the United States that broadly represent crustal zones intruded by significant volumes of silicic igneous rocks correlate in a rough way with regions of fluorine mineral deposits. Regions of high heat flow in the Western United States that reflect the middle Tertiary to present episode of magmatic and hydrothermal activity of this part of the country coincide remarkably with the regions of rather young fluorine mineral deposits. Available regional aeromagnetic data reveal that zones of numerous sharp positive anomalies (that represent in part intrusive igneous centers) coincide with the positions of fluorine mineral belts.

A broad region of low seismic velocity in the upper mantle in the Western United States closely encompasses the region of middle to late Tertiary magmatism and fluorine mineralization. Inferences on the composition of the low velocity upper-mantle material suggest that

volatile components composing fluorine-enriched magmas were fractionated out of the upper mantle and injected into the crust which accounts for the higher heat flow, the fluorine-rich igneous rocks, and the fluorine mineral deposits of the province. Plate tectonics is invoked to account for extension of the continental crustal plate beginning in middle Tertiary time; this extension was accompanied by conjugate strike-slip faulting in the lower part of the crust and tensional faulting in the upper part of the crust. Crustal extension resulted in a phase transformation in the upper mantle, which accounts for the development of fluorine-rich magmas that were injected upward into the crust and were accompanied by fluorine mineralization.

Fluorine mineral deposits that have had significant production or constitute a significant type are described in the text on the basis of geographic distribution and geologic environment. In the Lost River tin district, Seward Peninsula, Alaska, large carbonate-replacement and pipelike fluorspar deposits are associated with granitic intrusives. Elsewhere on the Seward Peninsula, fluorite occurs in other tin districts, in mineralized carbonate rocks north of Nome, in breccia pipes in the Kigluaik Mountains, and in carbonate rocks surrounding alkalic intrusives in the Darby Mountains. In other parts of Alaska, fluorite and topaz are associated with peralkalic granites and occur in some sulfide deposits. Large fluorine resources are known but currently inaccessible in marine phosphate rock in northern Alaska.

In the northwestern part of the United States, important fluorspar-producing areas are the Meyers Cove and Challis deposits, Idaho, where fluorite veins occur in volcanics and porphyries and in dolomite, respectively; and the Snowbird, Spar, and Crystal Mountain deposits, Montana, which are pegmatitelike bodies. Numerous other fluorspar deposits associated with volcanic rocks, granitic intrusive rocks, or alkalic rocks, or occurring as pegmatites or disseminated in granite are widespread in north-central Washington, central and southwestern Idaho, western to central Montana, several areas in Wyoming, and the Black Hills of South Dakota.

In the southwestern part of the United States manto replacement and pipelike bodies of fluorspar occur in limestone in the Fluorine district, Nevada; vein deposits are found in andesite and rhyolite at Broken Hills, Nev.; pipe deposits are known in carbonate rocks at Spor Mountain, Utah; and veins occur in volcanic rocks in the Indian Peak Range, Utah. Throughout much of Nevada, southeastern California, western Utah, and western Arizona numerous occurrences of fluorspar are known in veins, mantos, or pipelike bodies in and associated with volcanic rocks, in contact zones or stockworks of hypabyssal or plutonic igneous rocks, in volcanoclastic sediments, and in pegmatites. The Quinn Canyon Range district, the Wells Cargo deposit, and the Iowa Canyon deposits, Nevada, and the Castle Dome district, Arizona, offer promise of substantial fluorspar production.

The southern Rocky Mountain region of the Western United States in Colorado, New Mexico, western Texas, and southeastern Arizona contains numerous fluorspar deposits. Many deposits are characterized as layered or crustified veins in young steep tensional faults or breccia zones occurring in Tertiary volcanic rocks, Paleozoic or Mesozoic sedimentary rocks, or Precambrian silicic igneous or metamorphic rocks. Such veins are in the Northgate and Browns Canyon districts, and near Crystal, Dillon, Poncha Springs, and Wagon Wheel Gap, Colo., and the Gila, Burro Mountains, Anderson, Gold Hills, Steeple Rock, Sierra Caballos, Zuni Mountains, Fluorite Ridge, and Cooks Peak districts, and deposits at Tonuco, Tortugas Mountain, Bishop Cap, and Sierra Cuchillo, N. Mex. Manto deposits occur in carbonate rocks in the Sierra Caballos and Sierra Cuchillo, and at Tortugas and Bishop Cap deposits, New Mexico, and in the Eagle Mountains and Christmas Mountains-Corazones Peak districts in Texas. At the Jamestown district, Colorado, significant stockworks, pipelike shoots, and mineralized breccia zones, containing fluorite and lead, silver, gold, and uranium minerals, occur in Precambrian granite near a middle Tertiary alkalic-silicic stock.

In the Illinois-Kentucky district, large and numerous veins and replacement bodies of fluorspar, barite, and sphalerite occur in faulted

carbonate rocks in the vicinity of small mafic-alkalic dikes. These deposits have yielded more than 75 percent of the fluorspar mined in the United States. Large low-grade tonnages of fluorspar-mineralized breccia are known in the vicinity of Hicks dome, Illinois, but have not yet been developed.

In the Central and Eastern United States outside of the Illinois-Kentucky district, numerous fluorine mineral deposits are known and some offer promise of substantial fluorine resources. High-temperature veins, lodes, greisens, tactites, and skarns commonly containing fluorite and topaz and associated minerals of tungsten, tin, silver, gold, lead, zinc, molybdenum, iron, rare earths, and thorium, occur in the Appalachian structural belt, the Ozark dome, Missouri, and the Llano uplift, Texas.

Intermediate-temperature deposits are chiefly veins such as fluorite-quartz veins in the Cheshire County-Westmoreland district, New Hampshire, and complex fluorite-bearing veins near Faber, Va.; in the Connecticut Valley, Mass.; near Phoenixville, Pa.; on Deer Isle, Maine; and at Litchfield, Conn.

Most of the fluorspar deposits in the Central and Eastern United States are low-temperature veins, mantos, breccia bodies, stockworks, pipelike bodies, and disseminated deposits. The largest and most numerous deposits outside of the Illinois-Kentucky field, are in the Mississippi Valley and in the Appalachian Valley and Ridge province in the vicinity of related zinc deposits. Other Mississippi Valley-type districts are the Central Tennessee district, the Cumberland River district, the Central Kentucky district, and the Rossie area, New York. Deposits of the Valley and Ridge type are numerous along the Appalachian belt from Alabama into Pennsylvania in Cambrian-Ordovician carbonate rocks. The largest deposit is in the Sweetwater district in eastern Tennessee. Others are the Del Rio, Tenn., and Hot Springs, N. C., districts and the Gilley deposit in northeastern Alabama. Disseminated deposits are found in central Pennsylvania, northeastern New York, northeastern Iowa, northwestern Ohio, and southeastern Ohio.

Residual deposits of fluorspar are known in western Kentucky, central Kentucky, and central Tennessee, and placer deposits of topaz are known in South Carolina and in the Llano uplift of central Texas.

Economic fluorine-bearing phosphate deposits in the United States are confined to marine sedimentary phosphorites of Ordovician age in Tennessee, of Permian age in Idaho, Montana, Wyoming, and Utah, of Miocene age in North Carolina, Georgia, and South Carolina, and of Miocene and Pliocene ages in Florida. Fluorine content of the rock is about 3-4 percent, and billions of tons of phosphate resources are known.

Present and future resources of fluorine in the United States are evaluated in the light of past production. In the past most fluorine production has come from fluorspar, and fluorspar will continue to be the major source in the near future. Phosphate rock and other byproduct and coproduct sources will become increasingly important as fluorspar resources diminish. From 1900 to about 1950 the United States changed from a minor producer of fluorspar to the major world producer, but from 1950 to 1970 has reverted to the seventh or eighth leading producer. Production generally has risen in recent years, however, until it now averages about 200,000 short tons CaF_2 annually. Until about 1950 United States production of fluorspar nearly equaled its consumption, but since 1950 consumption has increased dramatically to nearly 1,500,000 short tons of CaF_2 annually. In addition, since 1950 worldwide fluorspar consumption has increased spectacularly to more than 4,500,000 short tons of CaF_2 annually, emphasizing the fact that the United States is faced with strong competition for foreign supplies of fluorspar.

United States reserves of fluorspar are about 25,000,000 short tons of crude ore (> 35 percent CaF_2). Hypothetical resources of fluorspar in the United States are about 45,000,000 short tons.

The marine phosphate rock deposits of Florida, North Carolina, Tennessee, Utah, Wyoming, Idaho, and Montana contain about one-third billion tons of fluorine in known reserves and about 2 billion tons of fluorine in identified resources. Marine phosphate rock thus constitutes by far the United States' and the world's largest fluorine resource.

Topaz reserves at the Brewer mine, South Carolina, are about 100,000 tons of schist averaging about 15 percent topaz; hypothetical resources are estimated at about 800,000 tons of rock. In the Front Range, Colo., a lens in Precambrian gneiss contains about 15 percent topaz and a reserve of about 600,000 tons of topaz-bearing rock. Byproduct resources of topaz and fluorite in molybdenum porphyry deposits at Climax and Henderson, Colo., and Questa, N. Mex., may constitute several million tons of fluorine.

Bastnaesite in carbonatite at Mountain Pass, Calif., contains an estimated 1,000,000 tons of fluorine and is a potential byproduct of rare-earth extraction.

Fluorine resources in the United States appear to be adequate for projected needs for many years into the future. Adequate sources of fluorspar are available for the present and near future; vast amounts of fluorine in marine sedimentary phosphate deposits are available as a more distant future resource, dependent on technological improvements in recovery.

Most fluorine mineral districts and localities in the United States remain as areas favorable for further exploration for fluorine resources. In productive districts extensions of known fluorspar bodies should be sought along strike and in depth, and additional ore bodies may be found along nearby faults. Carbonate rocks susceptible to replacement by fluorite should be explored, as deposits in such rocks tend to be large and amenable to large-scale low-cost mining. An increasingly important source of fluorspar will be as a coproduct from the mining of iron, base-metal, barite, and rare-earth ores.

More analyses for fluorine in earth materials should be made routinely to provide background and geochemical information as well as possibly to disclose new environments of fluorine mineral deposits.

Exploration for and evaluation of speculative fluorine resources—those occurring in districts and environments yet to be identified—must be based on knowledge of the geologic environment and the geochemical cycle of fluorine. Geologic mapping in areas not now adequately covered by geologic maps will be essential to evaluation of geologic environment and to successful exploration in such areas. Major geologic parameters that partly define the geologic environment of fluorine mineral deposits in western North America are: (1) extensional tectonism related to deep-seated, mainly northwesterly, northeasterly, and easterly strike-slip structures; (2) high heat flow from the mantle; and (3) magmatism of alkalic affinity characterized by fluorine abundance. These parameters define environments and processes in which fluorine was intrinsically available in abnormal amounts in some part of the system, and could be mobilized into economic concentrations. On the other hand, geologic processes in other environments have concentrated minor (crustal abundance) amounts of fluorine into deposits of economic interest, such as marine phosphate rocks. Earlier concentrations of fluorine may have been dispersed, or remobilized and reconcentrated in new environments by later processes.

In the Central and Eastern United States new districts of fluorspar in carbonate rocks may be found near Toledo, Ohio, near Serpent Mound, Ohio, in southern Indiana, in and near the Ste. Genevieve fault zone in southeastern Missouri and southern Illinois, along the Cumberland River, Ky., in central Tennessee and central Kentucky, and near Magnet Cove, Ark.

In the Western United States fluorspar deposits undoubtedly underlie parts of the widespread cover of Tertiary and Quaternary sediments and volcanics. Fluorite-bearing Cenozoic tuffaceous lake beds and other similar deposits in the Western United States may offer potential for large fluorine resources. Fluorspar deposits related to silicic-alkalic volcanic rocks in the Western United States may be found in the igneous areas of the Big Bend region of Texas, Nacimiento region of Arizona, New Mexico, and Colorado, and the Shoshone province of Nevada, Utah, Idaho, Wyoming, and Montana, particularly southeastern Idaho, northwestern Wyoming, and northwestern Utah. Caldera ring-fracture zones in addition to major deep-seated strike-slip fracture zones and major rift structures may be favorable for undiscovered fluorspar districts in these

regions. Deposits of syngenetic fluorite associated with marine gypsum and limestone of Permian age, like the deposits in north-central Wyoming, may be found elsewhere in the United States.

Large deposits of carbonate-fluorapatite in marine phosphate rock probably exist beneath the sea in Cenozoic coastal plain sediments extending east from the deposits in the Carolinas and Florida. Fluorine may be recoverable from deposits of fluorapatite in alkalic rocks and from deposits of fluorapatite and magnetite forming contact-metamorphic zones around intrusives.

Probably millions of tons of topaz-bearing rock are yet to be discovered in widespread metamorphic terranes throughout the United States, as well as in presently unknown molybdenum porphyry deposits. Inasmuch as cryolite for many years constituted a significant fluorine resource at Ivigtut, Greenland, it conceivably may occur in similar deposits elsewhere. Sodium fluoride in saline lake beds may some day be a source of fluorine. Many other very low-grade geologic sources of fluorine offer potential only for the distant future.

Some very large low-grade multicommodity ores, in which fluorine minerals are associated with metallic minerals, barite, rare-earth minerals, apatite, zeolites, feldspars and other minerals of commercial value, may become resources of fluorine.

Geochemical and geophysical prospecting methods may be valuable additional aids to apply to exploration for fluorine mineral resources. Geochemical techniques as well as panning are useful for detecting detrital fluorite that has been dispersed, in some cases as much as 35 miles, from its source. Some pathfinder elements such as zinc, silver, antimony, cadmium, gallium, germanium, vanadium, and molybdenum may be useful in geochemical prospecting for fluorine mineral deposits. Uranium identified by radiation detectors might also be a useful guide to fluorspar-uranium deposits. Fluorine anomalies may be guides to deposits of associated valuable minerals.

An induced activity method of measuring the short-lived isotope F^{20} after activation by a polonium-beryllium source offers promise of accurate in-hole measurement of fluorine content of rocks.

Earth-resistivity, refraction seismic, and self-potential geophysical methods have been used to detect structures that may contain fluorine mineral deposits. Induced potential methods may successfully outline alteration zones that are favorable for fluorine mineral deposits.

INTRODUCTION

By R. E. VAN ALSTINE

Fluorspar, the primary source of fluorine, is a vital and integral part of our economy, for it has great commercial and strategic importance because of its wide use in the metallurgical, chemical, and ceramic industries. Reviews (Industrial Minerals, June and July 1970) of the world's supplies of fluorspar predict shortages in the near future. The increased demand is chiefly the result of the change-over by the steel industry to the basic oxygen process requiring about three times as much fluorspar as conventional processes; continued expansion of the aluminum industry; and the growing market for fluorine chemicals, especially fluorocarbons (MacMillan, 1970). The expanding needs of these industries stimulated review of our fluorine resources.

This report is part of an effort by the U.S. Geological Survey to present comprehensive and updated information on the significant mineral resources of the United States, with appropriate reference to world resources. The expanding industrial needs for fluorine stimulated the present review of our resources. Particular attention is

given to the geochemistry of fluorine, for it defines and limits fluorine's geologic environment, and thus the origin, habit, and distribution of fluorine mineral deposits. Representative examples of the major types of deposits (fluorspar, calcium fluophosphate, topaz) and of other fluorine-bearing minerals are described in detail, by geographic area; many other deposits are described briefly, and references to sources of detailed information are given. In addition to this report, fluorine resources are also reported on briefly by Worl, Van Alstine, and Shawe (1973), and a map by Worl, Van Alstine, and Heyl (1974) shows distribution of fluorite in the United States. The map was intended as a supplement to the present report, and reference to it will be made in the following pages.

Continuing supplies of domestic and imported fluorspar are required to produce the variety of metals and materials essential to our industries (Bradbury and others, 1968, p. 35-60; Williamson, 1961). The United States consumption of fluorspar has doubled in the past decade and is expected to grow about 5 percent per year. About 80 percent of the fluorspar that we consume is imported, chiefly from Mexico, Spain, and Italy; fluorspar imports exceeded 1 million short tons for the first time in 1968. About 80 percent of our domestic fluorspar, totaling about 237,000 short tons in 1972, comes from the Illinois-Kentucky district, which has been the world's most productive district. Small quantities of fluorine compounds are produced as byproducts from the phosphate industry, and some fluorine is recovered by the aluminum industry from the waste streams of the Hall cell and by the chemical industry in plants producing hydrofluoric acid. These secondary sources of fluorine should provide for an increasing part of the fluorine supply as we become more concerned with reducing environmental pollution. Although fluorspar is still the primary source of fluorine, much more fluorine is lost in phosphate rock that has been mined than is recovered from fluorspar.

The National Materials Advisory Board (NMAB-269, 1970) estimated that annual consumption of fluorspar in the United States would increase by about one-fourth between 1970 and 1975, but by only one-fifth between 1975 and 1980.

As shown in the accompanying table, production of steel and hydrogen fluoride accounts for about 93 percent of the total domestic fluorspar consumption. This percentage is not expected to change greatly in the near

Consumption of fluorspar in the United States, in short tons

Use	1970	1975 (estimated)	1980 (estimated)
Steel production.....	548,700	723,000	895,000
Hydrogen fluoride production	726,500	920,000	1,160,000
Glass and enamels	35,000	35,000	35,000
Foundry.....	21,400	24,100	27,400
All other.....	35,000	45,000	56,000
Total.....	1,366,600	1,747,100	2,173,400

future, even though the requirements for the various uses are growing. In 1952 the President's Materials Policy Commission (Paley, 1952) predicted that the United States fluorspar consumption by 1975 would be 1.15 million short tons, a quantity that we have exceeded since 1968; this prediction is an example of the tendency to underestimate future resource needs.

In the United States about 3 tons of crude fluorspar is mined and beneficiated for each ton of finished product marketed. Fluorspar generally is sold in three grades—acid, ceramic, and metallurgical.

Acid-grade fluorspar should contain at least 97 percent CaF_2 . Limitations are sometimes put on SiO_2 , CaCO_3 , and sulfide sulfur. Chemical and physical requirements are given in National Stockpile Material Purchase Specifications P-69a-R1, June 1, 1967, General Services Administration.

Ceramic-grade fluorspar varies substantially with individual buyers but is usually finely ground and has a CaF_2 -content ranging from 85 to 97 percent. The Fe_2O_3 -content usually is limited.

Metallurgical-grade fluorspar in the form of gravel, lump, artificial pellets, or fine flotation concentrates contains at least 60 percent effective CaF_2 units, determined by subtracting from the contained CaF_2 2.5 percent for every percent of SiO_2 present in the complete analysis. National Stockpile Purchase Specification P-69b-R1, December 2, 1963, contains requirements for metallurgical-grade fluorspar.

Published prices (1973) per short ton were \$78.50-\$87.00 for acid-grade fluorspar, \$77-\$87 for ceramic-grade, and \$68.50 for metallurgical-grade pellets (70 percent effective CaF_2). The (1973) tariff on fluorspar containing more than 97 percent CaF_2 was \$1.875 per short ton and was \$7.50 per short ton on fluorspar containing less than 97 percent CaF_2 . CaF_2 percentages in this report are weight percentages.

In 1971 about 52 percent of the fluorspar consumed in the United States was acid grade, 43 percent was metallurgical grade, and 5 percent was ceramic grade (U.S. Bur. Mines, 1973). About 97 percent of the quantity consumed in 1968 was used in the following 15 States: California, Colorado, Delaware, Illinois, Indiana, Kentucky, Louisiana, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, Texas, and West Virginia (U.S. Bur. Mines, 1969).

GEOCHEMISTRY OF FLUORINE

By D. R. SHAWE

Fluorine has the atomic number 9, atomic weight 19.00 (lightest element of Group VII of the periodic table), and a valence of minus one in all naturally occurring compounds. It has no isotopes.

Having an ionic radius of 1.36A, the fluoride ion is "readily isomorphous with the hydroxyl ion, $(\text{OH})^{-1}$

(radius 1.40A), a fact of great importance in its geochemical occurrence and behavior. To a lesser degree, fluoride ion may isomorphously replace chloride ion, Cl^{-1} (radius 1.81A), and oxygen ion, O^{-2} (radius 1.40A)." (Fleischer and Robinson, 1963, p. 58).

Fluorine commonly is considered to be concentrated as a result of magmatic differentiation into silicic igneous fractions, residual solutions, and vapors (for example, Fleischer and Robinson, 1963); however, data compiled here suggest ambiguity in this conclusion. Although certain rhyolitic and granitic rocks, as well as most alkalic rocks, contain unusually high amounts of fluorine, some consanguineous suites of igneous rocks show higher fluorine contents in less silicic members, and alkalic suites do not necessarily contain greatest fluorine concentrations in their most differentiated rocks. Further, some hybrid granitoid rocks whose chemical character was strongly controlled by assimilation of wallrocks show a clear decrease in fluorine content with increasing silica content.

ABUNDANCE OF FLUORINE IN ROCKS

Averages of the fluorine contents of various igneous rocks are as follows:

Rock type	Fluorine, in parts per million (number of samples in parentheses)	
	Fleischer and Robinson (1963, tables I, II)	This report ¹
Extrusive:		
Basalt.....	380 (268)	510 (187)
Andesite.....	220 (83)	630 (85)
Rhyolite.....	700 (145)	780 (261)
Phonolite.....	930 (14)	.....
Intrusive:		
Gabbro.....	430 (47)	.....
Granite, ² granodiorite.....	840 (183)	.....
Alkalic rocks.....	960 (71)	³ 2,640 (100)

¹Average fluorine contents of igneous rocks compiled for this report include published data and many unpublished data in the U.S. Geological Survey files that are not specifically credited here.

²Fuge and Power (1969) reported a mean fluorine content of 1,395 ppm for 90 unaltered granites from southwest England.

³Gerasimovskiy and Savinova (1969) confirm the higher values for alkalic rocks given here.

Fleischer and Robinson (1963, p. 61), in noting that fluorine appeared to increase with increasing silica content of igneous rocks, commented on the unexpectedly low fluorine content of andesites and suggested a possible regional effect owing to the preponderance of Japanese andesites in their summary. A more detailed view of the data in the foregoing table, as presented in the next table, may clarify this and other discrepancies in the averages for certain rock types.

In all instances the discrepancy between data compiled by Fleischer and Robinson and data compiled in this report can be attributed to the inclusion of rocks of alkalic affinities in the groups with higher fluorine averages. For example, rocks such as alkali basalts at Craters of the Moon, Idaho, and basalts termed absarokites from the Mogollon Rim, Ariz., raise the average fluorine content of

Rock type	Fluorine, in parts per million (number of samples in parentheses)	
	Fleischer and Robinson (1963, tables I, II)	This report ¹
Basalt:		
Aleutian Islands.....	.....	290 (13)
Hawaii.....	340 (80)	320 (71)
Snake River Plain.....	.....	400 (26)
Columbia River Plateau.....	.....	440 (20)
Puerto Rico.....	.....	460 (5)
Other.....	500 (58)	920 (52)
Andesite:		
Japan (dominantly).....	210 (77)	.....
Aleutian Islands.....	.....	250 (12)
Other.....	.....	² 700 (73)
Rhyolite:		
Alkali rhyolite.....	.....	³ 2,180 (25)
Other.....	700 (145)	630 (236)
Alkalic rock (mostly intrusive):		
Syenite, nepheline syenite (dominantly).....	960 (71)	.....
Rapakivi granite, mafic alkalic rock (dominantly).....	.....	2,640 (100)

¹Compilation includes most of the rocks analyzed by the U.S. Geological Survey that were averaged by Fleischer and Robinson, plus additional ones, and also some data reported in the literature but not summarized by Fleischer and Robinson.

²Includes latite and trachyte in silica range 55-65 percent.

³Idaho, Wyoming, Nevada, Utah, Arizona, New Mexico.

"other" basalts shown under "This report" in the preceding table. In contrast, basalts from Iceland have an extremely low fluorine content (180 ppm, average of 5; Barth, 1947). Although andesites from the Aleutian Islands and Japan have similar fluorine contents of about 200-250 ppm, the average content for the group of "other" andesites compiled for this report is appreciably higher because more alkalic types (latites and trachytes) that have the same silica range as andesite were included. In Fleischer and Robinson's compilation of data on alkalic rocks, syenites and nepheline syenites dominate, whereas in the compilation for this report the alkalic rocks are chiefly rapakivi-type granites and mafic alkalic rocks that appear to contain significantly more fluorine than do syenites. Virtually no duplication is involved in the two compilations in this case.

Fluorine tends to increase with silica in glassy volcanic rocks (Shawe and Bernold, 1966, pl. 5-C). Those data are summarized in the following table:

Fluorine content of glassy volcanic rocks

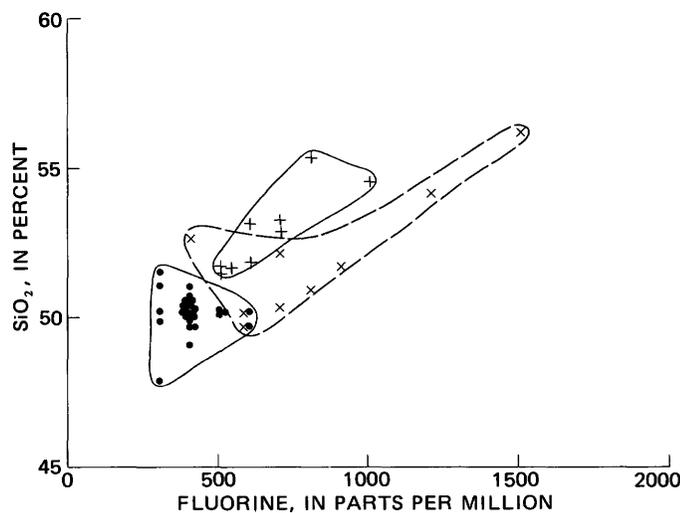
Silica range	Fluorine, in parts per million (number of samples in parentheses)
75-80 percent.....	1,040 (88)
70-75.....	670 (49)
65-70.....	580 (13)
45-65.....	340 (7)

Some workers (for example, Coats and others, 1963, p. 963) have considered that volcanic glasses, having been cooled quickly, closely reflect original magma composition. If so, the previous table strongly indicates that fluorine is concentrated in later fractions by magmatic differentiation.

Virtual proof of the concentration of fluorine in igneous rocks by magmatic differentiation is afforded by the data

of Wright (1971) and Wright and Fiske (1971). Twenty-nine olivine basalts from the summit of Kilauea, Hawaii, that are considered to be undifferentiated, range from 47.9 to 51.6 percent silica and contain an average of 410 ppm F (Wright, 1971, table 4). Nine other basalts from Kilauea classified as having formed by differentiation from magma chemically similar to basalts of the summit of Kilauea, on the basis of their general chemistry and geologic occurrence, range from 51.5 to 55.4 percent silica and contain an average of 660 ppm F (Wright and Fiske, 1971, table 13). Also, nine samples of "differentiates"—gash fracture fillings in natural flows, or material that flowed into open drill holes in flow crusts ("oozes")—that range from 49.6 to 56.2 percent silica contain an average of 820 ppm F (Wright and Fiske, 1971, app. 3, table 1). These data are presented graphically in figure 1.

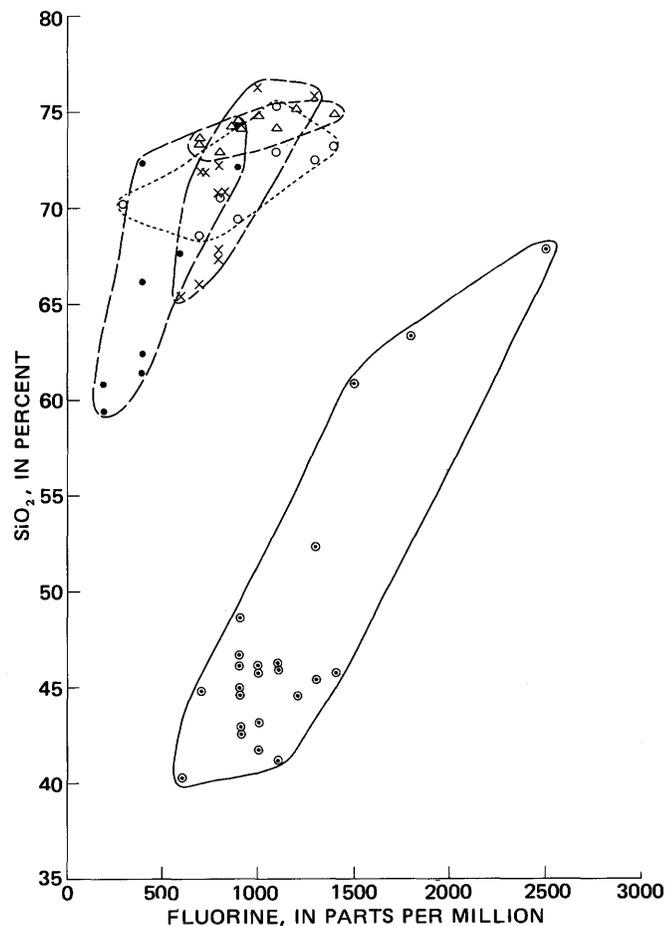
Certain other suites of igneous rocks from various parts of the world also exhibit a tendency for fluorine to increase along with silica, suggesting concentration by magmatic differentiation (fig. 2). Of the examples shown, however, rocks of the Hallett volcanic province, Antarctica, were considered by Hamilton (1972, p. 59) to represent two divergent petrologic series, and rocks from the Egan Range, Nev., constitute two groups (one high in fluorine, one low), believed by Shawe (1961, p. B181) not to be closely related genetically.



EXPLANATION

- Olivine basalt, Kilauea Summit (Wright, 1971, table 4)
- + Differentiated lavas, Kilauea (Wright and Fiske, 1971, table 13)
- × Kilauea "differentiates" (Wright and Fiske, 1971, appendix 3, table 1)

FIGURE 1.—Positive correlation between fluorine and silica contents of olivine basalt from Kilauea Summit, differentiated lavas of Kilauea, and Kilauea "differentiates," Hawaii.



EXPLANATION

- Egan Range, Nevada (Shawe, 1961, table 1)
- Mountain City-Owyhee, Nevada (R. R. Coats, unpub. data)
- × Schell Creek Range, Nevada (Drewes, 1967, tables 10, 11, 12)
- ◉ Hallett volcanic province, Antarctica (Hamilton, 1972, tables 2, 3)
- △ Black Hills, South Dakota (Norton, 1970, table 2)

FIGURE 2.—Positive correlation between fluorine and silica contents of five igneous suites.

In comparisons of fluorine content with beryllium content (and indirectly with silica content) of volcanic rocks, Griffiths and Powers (1963, p. B18-B19) and Shawe and Bernold (1966, p. C8) suggested that positive correlations were poor within a group of genetically related rocks, but relatively good overall among samples from many populations (that is, genetically unrelated rocks).

Other data, presented by Shawe and Bernold (1966, pl. 5-A), surprisingly show a negative correlation between

fluorine and silica contents of volcanic tuffs, as summarized in the following table:

Fluorine content of volcanic tuffs

Silica range	Fluorine, average in parts per million (number of samples in parentheses)
75-80 percent.....	420 (20)
70-75.....	700 (24)
65-70.....	700 (22)
60-65.....	900 (5)

Most of the tuffs summarized in the above table are from the Nevada Test Site, southern Nevada, and the table thus generally represents a single igneous petrographic province. Many of the tuffs are zeolitized, but it is not known if zeolitization had any effect on fluorine content of the rocks.

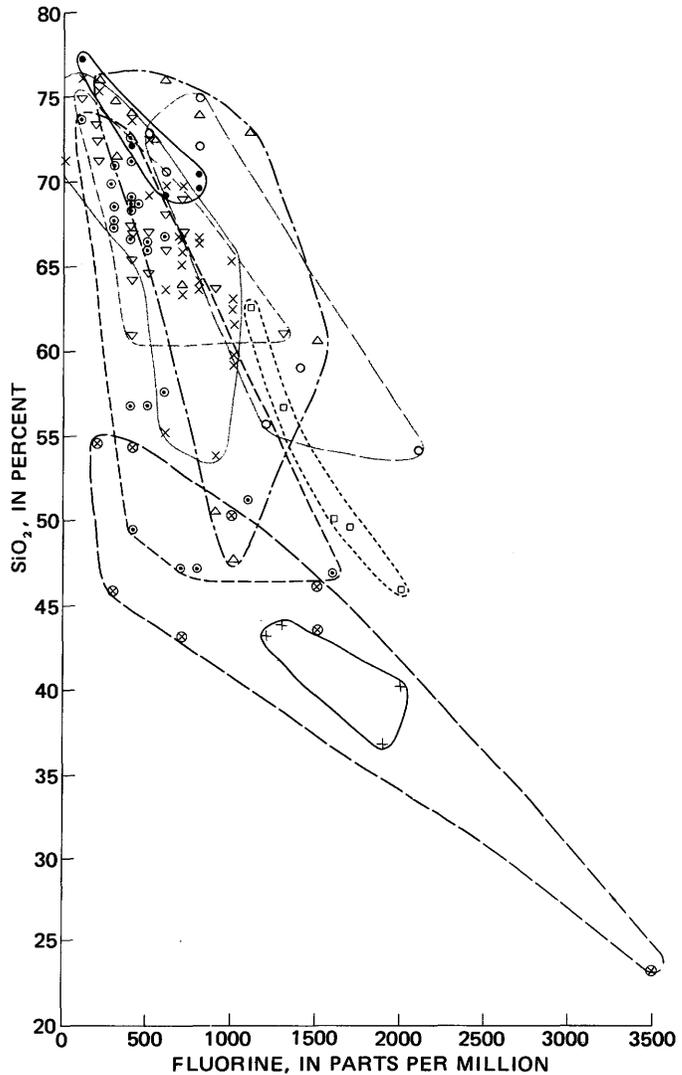
Other examples of inverse silica-fluorine relations among rocks in consanguineous series are illustrated in figure 3. Not every example here necessarily represents a comagmatic series, but each example does represent a suite of igneous rocks generated in a unique segment of the crust or upper mantle, a fact reflected by the coherency of the field for each example shown. A special case is presented by the field for rocks from the Valley of Ten Thousand Smokes, Alaska (Lovering, 1957, table 1), in figure 3; most samples are hydrothermally altered ash and thus the negative fluorine-silica correlation here is not directly attributable to magmatic processes.

An inverse silica-fluorine relation is shown in yet another assemblage of volcanic rocks. Basalts and andesites—excluding basalts from the Aleutian Islands, Hawaii, the Snake River Plain, Idaho, the Columbia River Plateau, Wash., and Puerto Rico, which plot in restricted fields lying mostly between 45-55 percent silica and 100-600 ppm F—are shown in a much broader field in figure 4. The strong tendency for higher fluorine to correlate with lower silica is summarized as follows:

Fluorine content of basalts from the Western United States and Antarctica

Silica range	Fluorine, average in parts per million (number of samples in parentheses)
60-65 percent.....	100 (1)
55-60.....	510 (13)
50-55.....	860 (8)
45-50.....	1,110 (17)
40-45.....	1,040 (13)
35-40.....	1,900 (1)

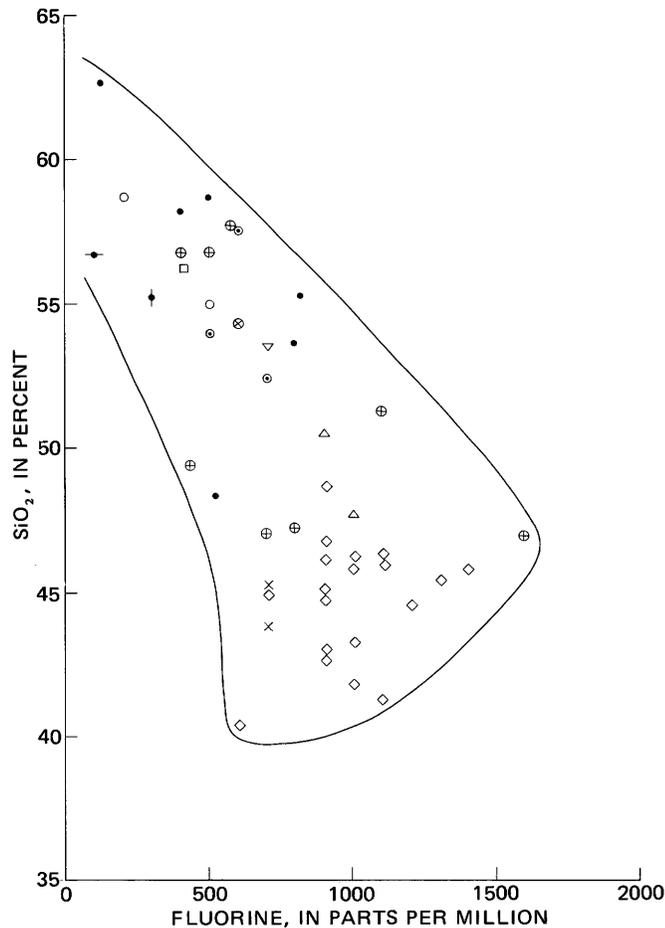
Lee and Van Loenen (1971) have shown convincingly that the composition of hybrid Jurassic granitoid rocks in the southern Snake Range, Nev., was closely controlled by the composition of assimilated wallrocks. This suite of related igneous rocks whose compositions vary serially and hence suggest origin through magmatic differentiation are thus shown to have developed probably simul-



EXPLANATION

- Railroad district, Nevada (K. B. Ketner and J. F. Smith, Jr., unpub. data)
- Valley of Ten Thousand Smokes, Alaska (hydrothermally altered ash; Lovering, 1957, table 1)
- × Creede-Summitville, Colorado (Steven and Ratté, 1960 tables 2, 3, 7; Ratté and Steven, 1967, tables 2, 4, 6, 14, 18, 22)
- ⊙ Funeral Peak, California (Drewes, 1963, table 4)
- △ Bullfrog, Nevada (Cornwall and Kleinhampl, 1964, table 2)
- Craters of the Moon, Idaho (H. A. Powers, J. G. Murtaugh, unpub. data)
- + Mogollon Rim, Arizona (T. L. Finnell, unpub. data)
- ⊗ San Gabriel Mountains, California (G. J. Neuberger, unpub. data)
- ▽ Mount of the Holy Cross Colorado (Ogden Tweto, unpub. data)

FIGURE 3.—Negative correlation between fluorine and silica contents of nine igneous suites from the United States.



EXPLANATION

- △ Basalt, Bullfrog, Nevada (Cornwall and Kleinhampl, 1964, table 2)
- Basalt, Cortez, Nevada (Gilluly and Masursky, 1965, p. 73: table 9)
- ⊙ Andesite, Klondyke, Arizona (Simons, 1964, p. 71, 72, 90)
- × Basalt, southeastern New Mexico (C. L. Jones, unpub. data)
- ⊗ Basaltic andesite, Steamboat Springs, Nevada (White and others, 1964, table 1, analysis 14)
- Basalt and andesite, Blue Range, Arizona and New Mexico (Ratté and others, 1969, table 6)
- Basaltic andesite, Twin Buttes, Arizona (J. R. Cooper, unpub. data)
- ▽ Basalt, Horse Creek Valley, Nevada (Harold Masursky, unpub. data)
- ⊕ Olivine basalt and andesite, Funeral Peak, California (Drewes, 1963, table 4)
- Basalt, Lassen County, California (R. L. Smith, unpub. data)
- † Basalt, South Victoria Land, Antarctica (W. B. Hamilton, unpub. data)
- ◇ Olivine basalt and trachybasalt, Hallett volcanic province, Antarctica (Hamilton, 1972, tables 2, 3)

FIGURE 4.—Negative correlation between fluorine and silica contents of basalts and andesites from the Western United States and Antarctica.

taneously through assimilation of chemically contrasting wallrocks. In the granitoid rocks, fluorine varies inversely with silica (fig. 5). Lee and Van Loenen (1971, table 9) showed that the quartzite wallrocks adjacent to the high-silica granitoid rocks contain an average 200 ppm F whereas the shale and limestone wallrocks adjacent to the low-silica granitoid rocks contain an average 1,300 and 600 ppm F respectively. According to Lee and Van Loenen (1970, p. D199), most of the fluorine in the granitoid rocks is in biotite. Biotite content varies from less than 5 weight percent in rocks of about 75 percent silica to more than 25 percent in rocks of about 65 percent silica. Interestingly, fluorine content of the biotite is highest (about 10,000 ppm) in rocks of about 75 percent silica and lowest (2,500–5,000 ppm) in rocks of about 65 percent silica. These relations suggest that the biotite took up what fluorine was available in the magma as it crystallized. Moreover, it appears that biotite in the more mafic rocks could have taken up more fluorine had it been available. Total fluorine content of these rocks thus depended on total fluorine available in magma and assimilated wallrock, and amount of biotite formed from the magma. Despite the likelihood of some initial fluorine in the magma, the data indicate that fluorine distribution in comagmatic igneous rocks of different composition need

not be wholly dependent upon magmatic differentiation.

Aplites in the southern Snake Range that are younger than the granitoid rocks just discussed, and that were intruded probably without appreciable assimilation, show a different fluorine-silica relation and therefore a different origin from that of the granitoid rocks (fig. 5).

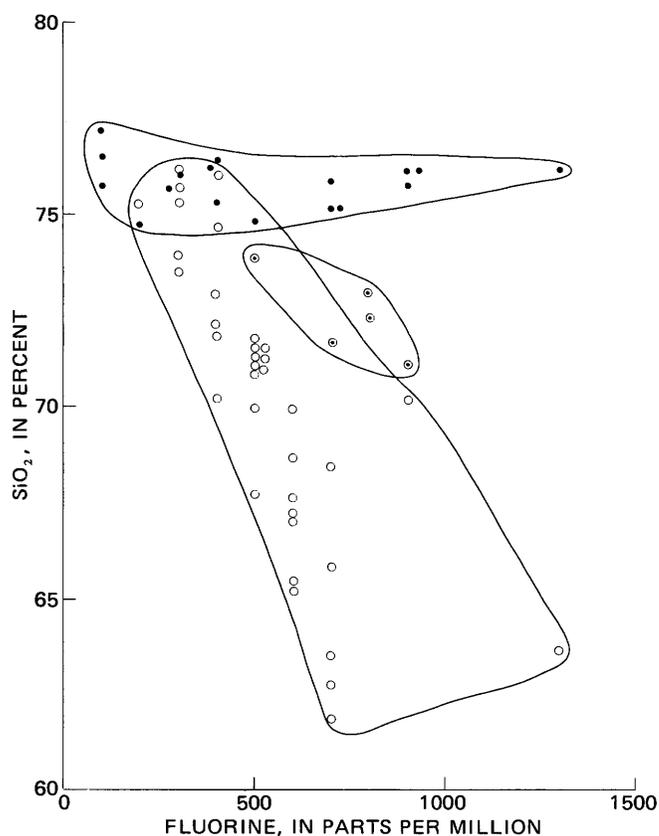
Fleischer and Robinson (1963, p. 63) indicated an average of 380 ppm F for 69 metamorphic rocks of a variety of types.

Sedimentary rocks, except for shales, oceanic sediments, and phosphorites, contain generally lower amounts of fluorine than do igneous rocks, as shown in the following table based mostly on Fleischer and Robinson (1963, table IV).

Rock type	Fluorine, average in parts per million (number of samples in parentheses)
Limestone.....	220 (98)
Dolomite	260 (14)
Sandstone and graywacke.....	200 (50)
Shale.....	940 (82)
Oceanic sediments.....	730 (79)
Volcanic ash and bentonite	750 (270)
Evaporites.....	200 (30)
Coal.....	150–190 (10)
Phosphorite.....	231,000 (60)

¹ Range for coals of Southwestern United States used in 10 powerplants, according to Swanson and Vine (1972).

²Average for Phosphoria Formation, Western United States, (Gulbrandsen, 1966, table 1).



EXPLANATION

- Aplite (Oligocene) of Pole Canyon–Can Young Canyon area (Lee and Van Loenen, 1971 table 10)
- Quartz monzonite (Jurassic) of Pole Canyon–Can Young Canyon area, (Lee and Van Loenen, 1971, table 6)
- Granodiorite and quartz monzonite (Jurassic) of Snake Creek–Williams Canyon area (Lee and Van Loenen, 1971, table 5)

FIGURE 5.—Correlation between fluorine and silica contents of hybrid granitoid rocks of Jurassic age and of aplite of Oligocene age from the southern Snake Range, Nevada.

Carpenter (1969) indicated that the average fluorine contents of recent oceanic sediments range between 450 and 1,100 ppm. Sediments from freshwater lakes have similar fluorine contents. Analyses of some mineral components of sediments indicate averages ranging from 50 ppm F (opal) to 1,560 ppm F (glaucinite); carbonate minerals ranged from 280 to 1,075 ppm F (Carpenter, 1969, table 2).

According to J. B. Cathcart (oral commun., 1973), the high amount of fluorine in phosphorite may be due in part to the “stripping” of traces of F^{-1} from ground water by calcium phosphate minerals after sedimentation and burial.

Soils, which average 285 ppm F in 327 samples, are richest in fluorine where they are high in clays, phosphate, or micas (Fleischer and Robinson, 1963, p. 66). Analyses by the U.S. Geological Survey's Washington laboratory of 959 soil samples collected by H. T. Shacklette in a study of the geochemistry of soils throughout the United States

indicate an average content of 291 ppm F (H. T. Shacklette, written commun., 1973). These values are substantially below the averages for most crustal rocks.

On the basis of average fluorine contents of igneous rocks, Fleischer and Robinson (1963, p. 67) estimated the average content of the continental crust to be 650 ppm. The average fluorine content of 533 volcanic rocks (rhyolites, andesites, and basalts) compiled for this report is 660 ppm, which is perhaps fortuitously close to the crustal estimate of Fleischer and Robinson.

ABUNDANCE OF FLUORINE IN GASES AND WATERS

Some gases and waters of volcanic origin long have been acknowledged as containing large amounts of fluorine (Zies, 1929; Fenner, 1933). Zies estimated large tonnages of fluorine being exhaled from cooling volcanic tuff in the Valley of Ten Thousand Smokes, Alaska, and Fenner, quoting Perrét (1924) and other early observers, described vast volumes of fluorine-bearing gas and extensive fluorine-bearing sublimates given off in the eruption of Vesuvius and other Italian volcanoes. The hydrothermally altered volcanic rocks of the Valley of Ten Thousand Smokes contain fairly abundant fluorine (500–2,100 ppm, Lovering, 1957).

The hydrofluoric acid content of “active” gases from a number of volcanoes, given by White and Waring (1963, table 1) are as follows:

Volcano	Rock type	HF, in weight percent (number of samples in parentheses)
Hekla, Iceland.....	Basalt	trace (2)
Kliuchevskii, Kamchatka....	Basalt	1.6 (7)
Aso caldera, Kyushu	Basaltic andesite	.4 (1)
Vesuvius, Italy.....	Tephritic leucitite	.1 (1)
Showa-Shinzan, Hokkaido	Hypersthene dacite	2.5 (11)
Katmai, Alaska.....	Rhyolite	21 (9)

In a general way these data show an increase in fluorine content of gases evolved from volcanoes with successively higher silica contents, from basalt through dacite to rhyolite. The anomalously low hydrofluoric acid amount for the one analysis of gas from leucitite lava is not in keeping with the reports of large volumes of fluorine emanating from Vesuvius.

White and Waring (1963, table 2) also presented data on the hydrofluoric acid content of fumarole condensates from several volcanoes, as summarized here:

Volcano	Rock type	HF, in milligrams per litre of water (number of samples in parentheses)
Hekla, Iceland.....	Basalt	13 (1)
Santa Maria, Guatemala....	Andesite	20.4 (1)
Sheveluch, Kamchatka.....	Andesite	38 (4)
White Island, New Zealand	Hypersthene andesite	69 (7)

Additional data on fumarole condensates (White and Waring, 1963, table 3), expressed in a different way, are:

Volcano	Rock type	Fluorine, in parts per million (number of samples in parentheses)
Kilauea Iki, Hawaii.....	Basalt	20 (1)
Ebece, Kurile Islands.....	Augite andesite	2.4 (1)
Showa-Shinzan, Hokkaido.....	Hypersthene dacite	195 (1)

Again, fluorine content seems to increase with increasing silica content of the source lava, from basalt through andesite to dacite.

Sublimates of volcanic fumaroles and eruption clouds were also reported by White and Waring (1963, table 5):

Volcano	Rock type	Fluorine, in weight percent (number of samples in parentheses)
Paricutin, Mexico.....	Basalt-andesite	0.55 (2)
Bezmyannyi, Kamchatka....	Andesite	.0067 (1)
Valley of Ten Thousand Smokes, Alaska.....	Rhyolite	14.9 (1)

The general fluorine-silica correlation is evident here, too.

Pertinent to the probable occurrence of fluorine-bearing condensates associated with volcanic materials are the data on fluorine content of tephra erupted from the volcano Hekla, Iceland, in 1970. Thorarinsson (1970, p. 47) reported as much as 2,000 ppm F in silicic tephra erupted in early phases of the 1970 eruption. This is a notably high amount compared to the 180 ppm average for Iceland basalts (Barth, 1947). Much of the fluorine in the silicic tephra was probably in the form of a readily soluble condensate, inasmuch as surface waters have rapidly leached fluorine from tephra shortly after Hekla eruptions (Stefánsson and Sigurjónsson, 1957).

The fluorine contents of gases extracted from igneous rocks, presented by White and Waring (1963, tables 6, 7), are summarized below:

Rock type	F ₂ , in volume percent (number of samples in parentheses)
Basalt.....	6.16 (8)
Andesite, dacite.....	2.03 (5)
Obsidian.....	3.19 (6)
Granite.....	2.27 (2)

Here there appears to be no correlation of fluorine with silica, and basalts appear to contain gases carrying rather high amounts of fluorine.

White and Waring (1963, table 4) gave the following data on the variation in fluorine content with temperature of fumarolic gases of Showa-Shinzan:

Temperature, °C	Fluorine, in parts per million
760°	238
525°	169
220°	35

A clear decrease in fluorine content with falling temperature is evident.

White, Hem, and Waring (1963, tables 1-27) compiled data on the fluorine content of subsurface waters. The data for ground waters collected in specific rock types, or as specific water or environment types are summarized in the following list:

Rock or water type	Fluorine, average in parts per million (number of samples in parentheses)
Granite, rhyolite, etc.....	0.9 (14)
Gabbro, basalt, ultramafic.....	.2 (12)
Andesite, diorite, syenite.....	.1 (4)
Sandstone, arkose, graywacke.....	.4 (16)
Siltstone, clay, shale.....	.6 (18)
Limestone.....	.3 (14)
Dolomite.....	.6 (5)
Other sedimentary rocks.....	.4 (4)
Quartzite, marble.....	.2 (7)
Other metamorphic rocks.....	1.3 (13)
Unconsolidated sand and gravel.....	2.6 (16)
Sodium chloride connate waters.....	3.1 (5)
Sodium and calcium chloride connate waters..	2.0 (3)
Sulfate-bicarbonate connate waters.....	4.5 (7)
Spring waters similar to sodium chloride connate waters.....	2.1 (5)
Spring waters similar to sodium and calcium chloride connate waters.....	1.3 (6)
Thermal waters, volcano-associated geysers.....	36.1 (12)
Thermal sodium chloride-bicarbonate volcano-associated waters (nongeyser).....	44.1 (6)
Volcano-associated acid sulfate-chloride springs.....	28.4 (3)
Volcano-associated acid sulfate springs.....	.6 (6)
Sodium bicarbonate-boron spring waters.....	.5 (5)
Thermal waters associated with epithermal mineral deposits.....	5.4 (11)
Non-thermal saline acid waters from mines, etc.	2.3 (3)
Travertine-depositing spring waters.....	4.2 (5)
Thermal waters probably meteoric in origin....	.3 (3)
Saline waters associated with salt deposits, etc.....	7.7 (8)

¹Excludes one water sample containing 4.0 ppm F collected from hornblende gneiss, Transvaal, Republic of South Africa.

²Excludes one water sample containing 24 ppm F collected from lake beds, Bruneau, Idaho.

³Five waters associated with rhyolite, dacite, and other silicic volcanic rocks average 10.0 ppm F; 7 waters associated with andesite and basalt average 3.4 ppm F.

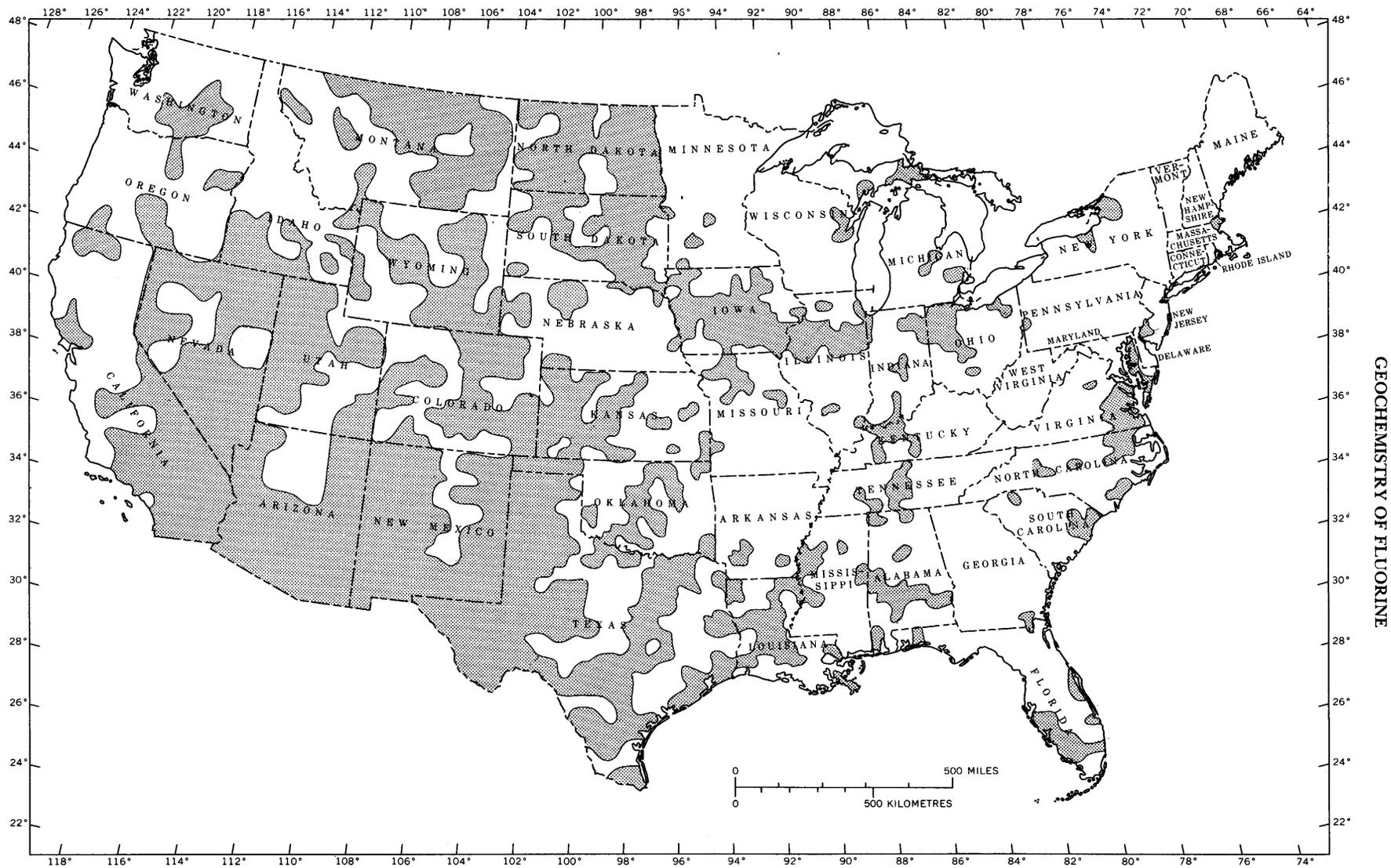
⁴Four waters associated with rhyolite average 5.8 ppm F; 2 waters associated with andesite and basalt average 0.8 ppm F.

⁵Excludes one strongly acid hot-spring water sample containing 806 ppm F collected from White Island (andesitic volcano), New Zealand.

As seen from the preceding list, the fluorine content of waters collected from specific rock types in general reflects the relative abundance of fluorine in those types of rocks. The average fluorine content of 123 water samples from all rock types is 0.4 ppm. Connate waters of all types contain much higher amounts of fluorine; 26 samples average 2.7 ppm. Still higher are thermal waters associated with volcanoes and epithermal mineral deposits, and related waters; 51 samples average 5.4 ppm F. Notably nine thermal waters associated with silicic volcanoes average 8.1 ppm F whereas nine thermal waters associated with mafic volcanoes average 2.8 ppm F.

Fleischer and Robinson (1963, fig. 3) showed the distribution of fluoride content of ground waters, by counties, in the United States. A generalization of their map is shown as figure 6. Significance of the data in figure 6 is discussed in the following section on the geochemical cycle of fluorine.

Livingstone (1963, tables 6, 7, 9-16, 18, 23, 25, 26) presented data from which it is computed that river and



GEOCHEMISTRY OF FLUORINE

FIGURE 6.—Distribution of fluoride content of ground water in the United States, generalized from Fleischer and Robinson (1963, fig. 3). Shaded areas indicate 1.5 ppm or higher in ground water.

lake waters of North America have an average fluorine content of 0.25 ppm (101 samples). (Compare Correns' (1956) estimate of 0.26 ppm F as the mean content of river waters.) Livingstone (1963, p. G41) also computed from the data of Konovalov (1959) that the mean fluorine content of rivers in most of the U.S.S.R. is about 0.09 ppm.

Only the Rio Grande system seems abnormally high in fluorine among the systems averaged in the North American estimate given in the preceding paragraph. Nine samples average 0.6 ppm F (Livingstone, 1963, table 16).

In addition, 7 samples of surface waters from Devils Lake basin, North Dakota, have an average fluorine content of 1.2 ppm, and 11 samples of surface waters from the Basin-Range province (as defined by Gilbert, 1928, p. 1) and adjacent closed basins have an average fluorine content of 5.3 ppm (Livingstone, 1963, tables 20, 19).

Fleischer and Robinson (1963, p. 72) on the basis of newer data endorsed the value of 1.2 mg/l (milligrams per litre) (1.2 ppm essentially) for the fluorine content of Pacific and Atlantic sea waters given by Thompson and Taylor (1933).

GEOCHEMICAL CYCLE OF FLUORINE

A review of the foregoing data allows some generalizations on the geochemical cycle of fluorine, but because data are incomplete or lacking on many aspects of the problem, much uncertainty remains.

Fluorine contents seem to be lowest in igneous rocks that have been irrupted through oceanic crust, such as andesites and basalts in the Aleutian and Hawaiian Islands and Iceland. The undifferentiated Hawaiian rocks clearly are derived from melting of the mantle, and the implication is that the fluorine content of the mantle is no higher than that of the basalts derived from it. Additional detailed chemical data on oceanic basalts other than Hawaiian are needed to indicate if mantle elsewhere in the world has similar fluorine compositions.

Some Hawaiian basalts that have migrated to shallow chambers have become differentiated before eruption, and this differentiation caused not only an increase in silica content, but also a substantial increase in fluorine content. It is evident that such magmatic differentiation does concentrate fluorine, as many earth scientists long have conjectured.

Basalts irrupted through continental crust tend to contain appreciably higher fluorine than do oceanic basalts. These continental basalts tend to have alkalic affinities; whether their higher fluorine content resulted from differentiation toward alkalic composition or from contamination by fluorine-enriched continental crust is a moot point. More data are needed on the fluorine content of alkalic rocks differentiated from mantle-derived basalts in the oceanic environment to test if differentiation or contamination might be dominant in the continental environment. Silicic rocks that contain high amounts of

fluorine also tend to be alkalic. Like the mafic rocks, those that show strong alkalic affinities tend to occur in continental environments. Even though differentiation toward silicic and alkalic types clearly does occur in the oceanic environment the process may be enhanced where it occurs in continental crust. Certainly, rocks—either silicic or mafic—that contain unusually high amounts of fluorine—5,000 ppm (0.5 percent) and higher—have formed in continental crust.

Although silicic igneous rocks as a whole average higher in fluorine than do mafic rocks, many silicic igneous rocks have fluorine contents as low as those that characterize most mafic rocks (fig. 7). The siliceous character of such rocks likely was not acquired through magmatic differentiation.

The data on distribution of fluorine in granitoid rocks of the southern Snake Range, Nev., indicate that fluorine content of the rocks was dependent on initial availability of fluorine and on the abundance of minerals that were capable of taking up fluorine. The negative correlation of fluorine and silica in numerous suites of igneous rocks thus might best be explained if their fluorine content represents that of the deep crust in which they were generated, and if they were not subject to strong magmatic differentiation after initial melting and before extrusion or emplacement in the upper crust. Such rocks likely changed composition substantially throughout their fluid history, but probably by assimilation of (reaction with) wallrocks rather than by fractional crystallization.

The evidence that crustal composition controlled fluorine content of some igneous rocks, and the strong association of fluorine with alkalic rocks, raise the question of the origin of alkalic rocks and the high concentrations of fluorine accompanying them. Without discounting the possibility of fractionating alkalic rocks from the mantle to account for their high alkali and fluorine contents, it seems quite possible that some alkalic rocks originated because alkalis became segregated and concentrated by the fluxing action of fluorine that was intrinsically high at a site of magma generation in the crust. Phosphatic rocks, for example, if melted, would develop a phosphate- and fluorine-enriched magma chemically similar to some known alkalic rock types. Some alkalic rocks therefore may reflect origin in fluorine-enriched segments of the crust, and their fluorine content may have been initial rather than a result of magmatic differentiation.

The fluorine content of metamorphic and sedimentary rocks is similar to that of most igneous rocks. If some igneous rocks are generated by melting of crustal rocks, including metamorphic, sedimentary, and preexisting igneous rocks, it is expectable that they contain generally similar amounts of fluorine. Conceivably some igneous rocks would contain less fluorine if it were driven off during melting that formed the magmas, and conceivably

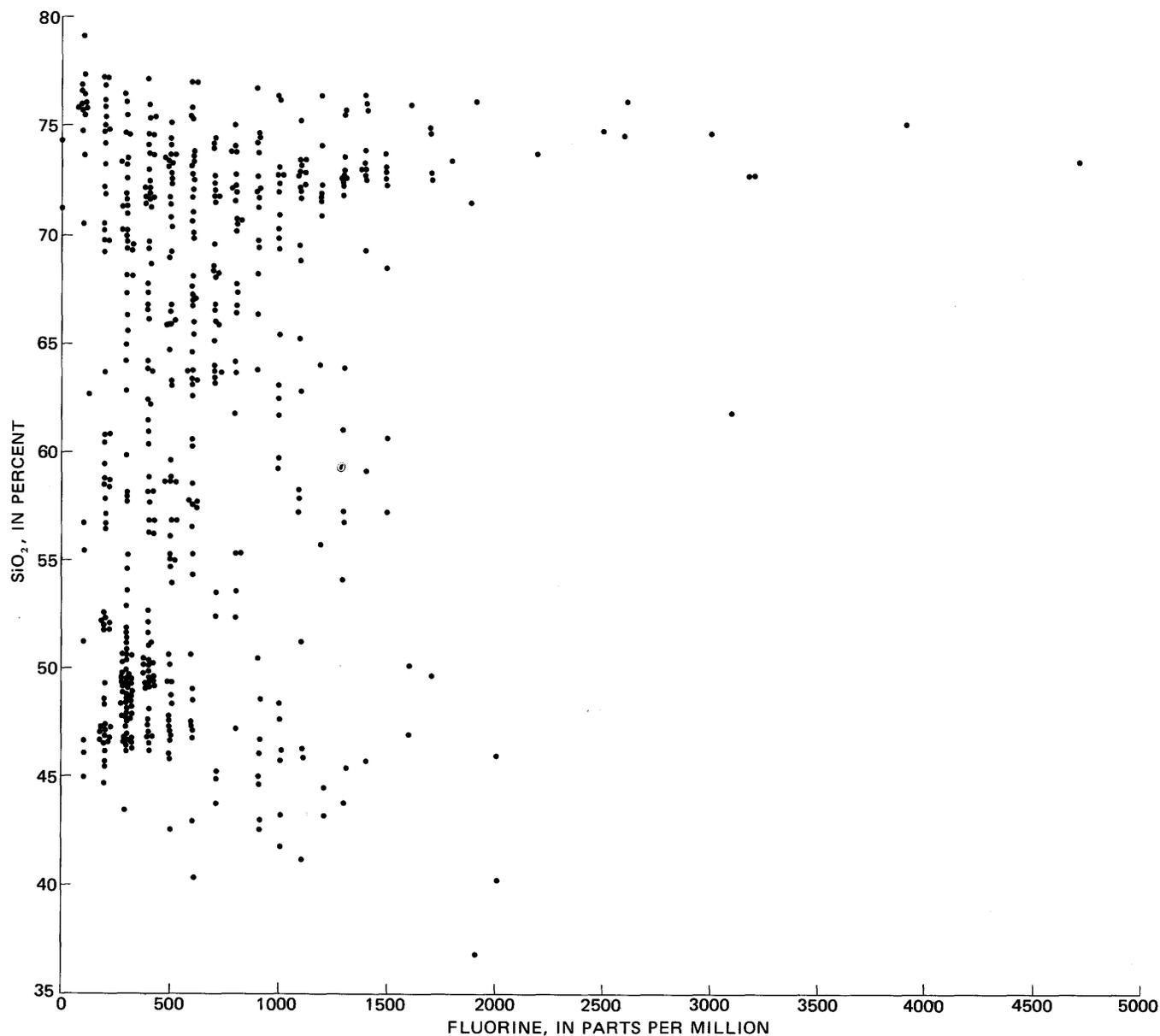


FIGURE 7.—Scatter diagram showing relation of fluorine to silica in 532 volcanic rocks. Data from published sources, and unpublished U.S. Geological Survey sources.

some igneous rocks would contain more fluorine if the parent rock contained unusual concentrations of fluorine.

The common occurrence of a bimodal assemblage of young alkali rhyolites and basalts, for example in the Western United States, both enriched in fluorine, provides insight into the cause of some fluorine enrichment. The basalts undoubtedly are mantle-derived; fluorine enrichment of a type such as that at Craters of the Moon, southern Idaho, could have occurred by differentiation following irruption of magma into a high level of the crust. A strong negative correlation of fluorine and silica in these rocks (fig. 3), however, suggests concentration of fluorine by a mechanism other than magmatic differentiation. The related alkali rhyolites in the same region,

compositionally akin to the young basalts and of similar age and geologic setting (erupted through tensional structures), likewise may have been mantle-derived. For such rhyolites to have been derived from the mantle, extreme fractionation of the more mobile and volatile components of mantle material must have occurred. Such fractionation by partial melting of mantle material could account for the unusually high fluorine contents of the rhyolites.

The fact that intrusive rocks tend to contain more fluorine than do extrusive rocks indicates that fluorine may be lost as a volatile component in a low-pressure environment. The data showing abundant fluorine in some volcanic exhalations corroborate this conclusion.

Some intrusive rocks are surrounded by halos of altered rocks in which fluorine is substantially enriched, suggesting that even magmas under relatively high pressures lose fluorine.

Analytical data on the fluorine content of volcanic gases, fumarole condensates and sublimates, and thermal waters associated with volcanoes, indicate a tendency for more fluorine to be exhaled by silicic volcanoes than by mafic ones. This relation is in keeping with the fact that silicic igneous rocks generally contain more fluorine than mafic igneous rocks, but more data are needed to correlate fluorine contents of exhalations directly with fluorine abundance in magmas. Data on the fluorine content of alkalic lavas and their exhalations particularly are needed. Nevertheless, it seems a fair conclusion that the higher the fluorine content of the magma, the more fluorine is given off in volatile phases, whether the magma is extruded or emplaced below the surface. Further, the temperature data from Showa-Shinzan, Hokkaido, suggest that the higher the temperature of the magma, the more readily fluorine is driven from the magma.

Whether a magma is intruded and cooled below the surface, or extruded, it seems clear that release of volatile components—including fluorine—from magma results primarily from pressure decrease, due to magma rise or rock fracturing. Crystallization of magma by itself would not be expected to drive off much fluorine, although the fluorine content of the residual magma would increase unless the minerals that crystallized included some capable of taking up fluorine (micas or amphiboles). Noble and others (1967) showed that devitrified silicic volcanic rocks have about half of the fluorine content of glassy equivalents (0.09 percent F, average of 89 samples, compared to 0.21 percent F, average of 72 samples), indicating that appreciable fluorine is lost upon crystallization (largely devitrification). This difference may be the result of lack of minerals in the crystallized silicic rocks capable of taking up fluorine.

The fact that soils average substantially lower in fluorine content than do rocks of the crust shows that fluorine tends to move into ground and surface waters during weathering.

Apparently ground waters generally dissolve fluorine from the rocks with which they are in contact in proportion to the abundance of fluorine in the rocks. For example, ground water in North Carolina and Virginia shows high fluorine contents only in areas where granites are known to contain fluorite. An arc extending from northwestern Ohio westward through Iowa and northward through the Dakotas has ground waters with high-fluorine content. The arc is underlain by glacial materials of the Mankato, Cary, and Tazewell Stages of the Wisconsin Glaciation, but not by those of the Iowan, Kansan, or Nebraskan Glaciations. Possibly the fluorine content of the waters can be related to the composition

of glacial material, or in a complex way to bedrock geology. In southern Arizona some areas where ground waters have high-fluorine values coincide with areas of volcanic rocks with high-fluorine contents.

Undoubtedly meteoric waters transfer some fluorine from the atmosphere (derived mostly from the oceans and in part from volcanic exhalations and industrial sources) to ground water near the Earth's surface, but data are needed to quantify the amount, seemingly less than that supplied to ground water from rocks.

Surface waters of the United States, composed of meteoric water mixed with a certain amount of fluorine-bearing ground waters, appear to stabilize with a fluorine content of about 0.25 ppm. These waters flow into ocean waters containing 4–5 times as high a concentration of fluorine, and thus tend to dilute the ocean waters.

Barth (1947, p. 422) argued that only a fraction of 1 percent of the fluorine derived from weathered and eroded rocks remains in solution after it reaches the sea; the rest is precipitated. According to Carpenter (1969) calcium carbonate precipitation dominates the removal of dissolved fluoride from sea water; precipitation of calcium phosphate undoubtedly removes substantial amounts.

Of course it is apparent that much fluorine is transported by rivers to the sea in suspension, contained in clay minerals that formed by weathering and in micas that are residual from weathering. Carpenter (1969) concluded that most of the fluorine which moves from the land to the sea does so in this fashion.

A comprehensive report on the geochemistry of fluorine (Koritnig, 1972) was published after this report was written.

ELEMENT ASSOCIATIONS

By R. E. VAN ALSTINE and D. R. SHAWE

Spectrographic analyses (Allen, 1952; Heyl, 1967, p. 25–26; Hall and Heyl, 1968, p. 658–661; Trace, 1960) reveal that minor elements associated with fluorite include aluminum, antimony, barium, beryllium, boron, carbon, cerium, copper, dysprosium, erbium, europium, gadolinium, iron, lanthanum, lead, lithium, lutetium, magnesium, manganese, neodymium, niobium, potassium, praseodymium, samarium, scandium, silicon, sodium, strontium, sulfur, terbium, thorium, thulium, tin, uranium, ytterbium, yttrium, zinc, and zirconium. In addition, galena associated with fluorite commonly contains silver and antimony, and the associated sphalerite generally contains cadmium, gallium, and germanium. The geochemical association of fluorine with beryllium in certain silicic volcanic rocks of the Western United States has been cited by Staatz and Griffiths (1961), Griffiths and Powers (1963), and Shawe and Bernold (1966). Coats, Goss, and Rader (1963) showed regional variations in the fluorine content of glassy rhyolitic volcanic rocks of the Western United States, and Coats (1956)

cited the correlation of fluorine and uranium contents in these Cenozoic volcanic rocks. Worl (U.S. Geol. Survey, 1970) found anomalous amounts of molybdenum in Precambrian wallrock next to the fluorspar deposits of the Northgate district, Jackson County, Colo. Altered wallrock contains as much as 800 ppm Mo, and the amount decreases away from the vein. For fluorite from Illinois, Virginia, and various districts of Colorado, New Mexico, and Utah, Blanchard (1966) gave the contents of strontium and yttrium, the two most abundant and widespread minor elements of the fluorite. Fluorite from the Illinois district (Ruch, 1968, p. 5) showed, in parts per million: < 0.04–0.60 scandium; 0.17–1.5 europium; 0.2–9.4 dysprosium; 0.2–4.1 samarium; 1–113 copper; 5–188 sodium; < 0.1–1.2 manganese; < 0.2–0.8 cobalt; < 1–10 chromium. Fleischer (1969, p. 36–37; table 1) pointed out that fluorite from granitic pegmatites contains notable concentrations of the heavy lanthanides (dysprosium, holmium, erbium, ytterbium, etc.) and fluorite from alkalic rocks contains notable concentrations of the light lanthanides (lanthanum, cerium, praseodymium, neodymium, etc.).

Perhac and Heinrich (1964, p. 238) listed cerium, lanthanum, praseodymium, neodymium, and samarium as the major rare-earth constituents of fluorite-bastnaesite ore in the Gallinas Mountains, N. Mex.

No clearcut preferred associations of fluorine with specific elements are evident from the foregoing data. Nevertheless, considerable data, both published and in the files of the U.S. Geological Survey, show that fluorine has a common association with a geochemically coherent group of elements including beryllium, lithium, manganese, niobium, tin, tungsten, uranium, yttrium, lead, and zinc. The data cited in the previous paragraphs are a catalog of a variety of types of associations: minor-element contents of fluorine minerals; minor-element compositions of rocks containing abnormal fluorine; and anomalous minor-element contents of rocks associated with fluorine mineral concentrations or ore bodies. This variety perhaps explains the lack of consistency in the data cited of association of fluorine with a specific suite of elements. On the other hand, geochemical data reveal a common association of fluorine with most or all of the elements of the assemblage beryllium-lithium-manganese-niobium-tin-tungsten-uranium-yttrium-lead-zinc in certain rock types, particularly alkali rhyolites (Shaw, 1966, p. C211) and granites (Hawley and others, 1966, p. C144, C145), and several fluorine-bearing ore types, including greisens (Hawley, 1969, p. A25, A31, A33, A36, A38; Sainsbury, 1964a), pegmatites (Norton and others, 1962, p. 111–118; Norton, 1970, table 2; Sheridan and others, 1957, p. 7, 16, 18), contact metamorphic aureoles (Sainsbury, 1964a; Warner and others, 1959, p. 114–116, 118, 122–125), certain veins (Sainsbury, 1964a, 1964b; Sainsbury, 1969, p. 68; Hewett, 1964, p. 1456), low-temperature stratiform

deposits in sedimentary rocks (Shawe, 1968, p. 1155), hot-springs deposits (Warner and others, 1959, p. 39; Hewett and Fleischer, 1960, p. 43; Hewett and others, 1963, p. 24, 26, 29–30), and saline lake brines.

GEOGRAPHIC DISTRIBUTION OF FLUORINE IN IGNEOUS ROCKS

By D. R. SHAW

Igneous rocks with high fluorine contents occur in two major geographically restricted areas in the United States, and are of two markedly contrasting ages. One area is a broad belt of dominantly Paleozoic rocks that extends from southern Maine southwestward into Alabama, and the other of dominantly Tertiary rocks that forms a U-shaped area extending from southwestern Montana southward through southern Idaho, eastern Nevada, and western Utah, into southern California, eastward through southern Arizona to southwestern New Mexico, and thence northward through western Colorado (fig. 8). Small patches of fluorine-rich igneous rocks occur elsewhere, notably in southern Illinois-southeastern Missouri and in central Arkansas.

The areas shown in figure 8 are somewhat generalized and are based on the known distribution of chemically analyzed igneous rocks containing 0.1 percent or more fluorine or microscopically recognizable fluorite or topaz. The rocks include alkali basalts and rhyolites (topaz-bearing rhyolites in part), alkali gabbros and granites, several other varieties of alkalic rocks, kimberlites, pegmatites, and greisenized granites. Many of these igneous rocks contain either fluorite or topaz as accessory minerals. Notably, in these fluorine-rich provinces mafic rocks as well as silicic rocks contain high amounts of fluorine.

Figure 8 also distinguishes zones, generally within the broad fluorine-rich igneous provinces, where fluorine-rich igneous rocks are especially abundant, or where some igneous rocks contain 0.2 percent or more fluorine or abundant fluorite or topaz.

Locations of topaz-bearing rhyolites are shown in figure 10.

Because of lack of data in places outside the areas of fluorine-rich igneous rocks shown on figure 8 some other fluorine-rich areas may exist but cannot be large.

In the Western United States a distinction can be made between fluorine-rich trachytes, trachybasalts, and phonolites of early to middle Tertiary age in central Montana, in parts of Wyoming, Colorado, and New Mexico, and in western Texas, and alkali rhyolites of middle Tertiary and younger age elsewhere throughout the Western United States fluorine-rich igneous rock province (Lipman and others, 1972, p. 222–226). In some parts of the Western United States fluorine-rich igneous rocks of Tertiary age are closely associated with older fluorine-rich igneous rocks. For example, phonolites of Tertiary age in the vicinity of Cripple Creek, Colo., are intruded into the

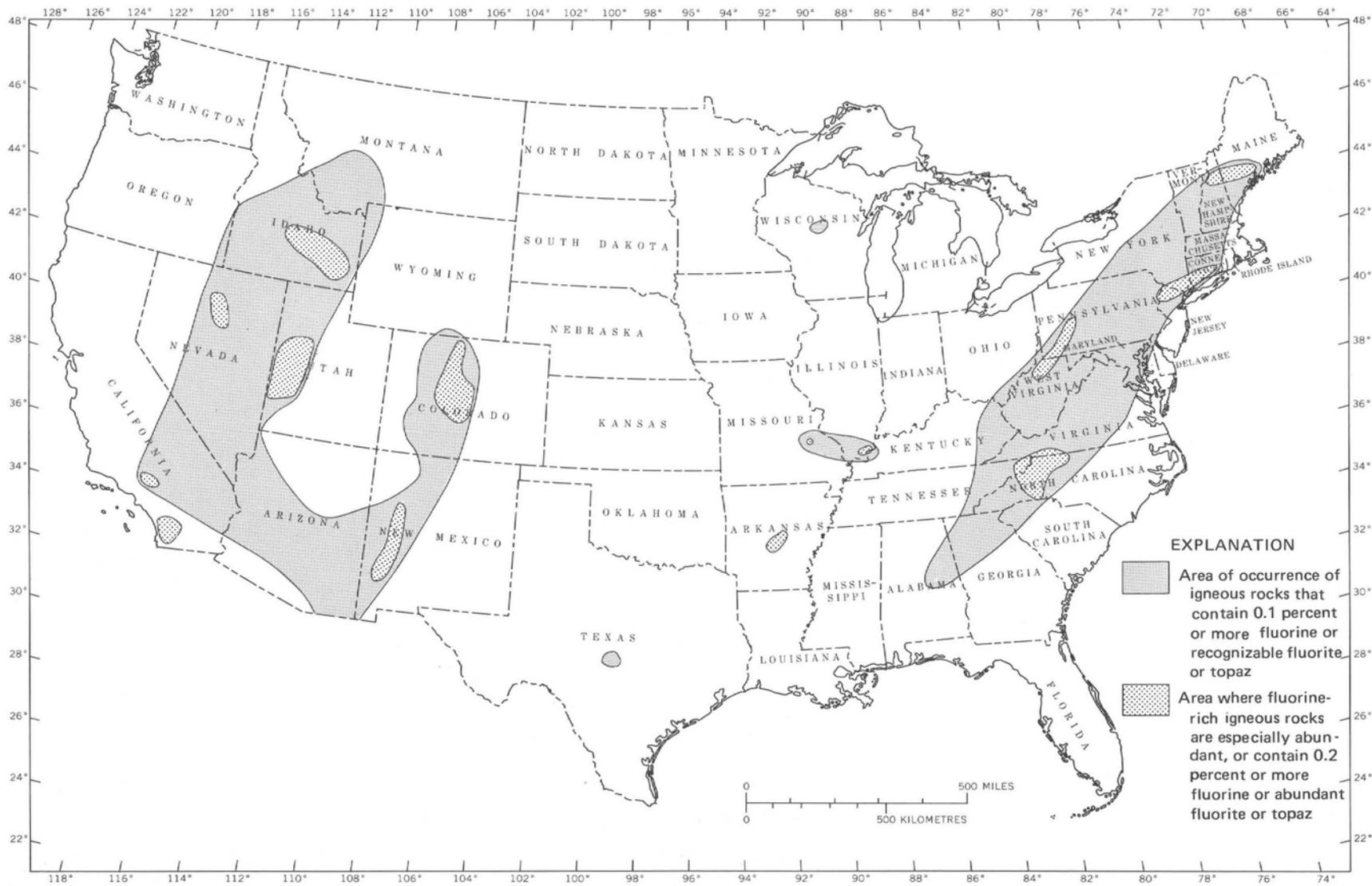


FIGURE 8.—Distribution of fluorine-rich igneous rocks in the United States.

Pikes Peak Granite of Precambrian age, suggesting the possibility that the high fluorine content of the Pikes Peak resulted in fluorine enrichment in the phonolites. Despite the presence of older fluorine-rich igneous rocks, the distribution of those of Tertiary age alone defines the extent of the fluorine-rich igneous province in the Western United States.

GEOLOGIC ENVIRONMENTS AND DISTRIBUTION OF FLUORINE

By D. R. SHAWE and R. E. VAN ALSTINE

Fluorine concentrations occur in a wide variety of geologic environments and in a multitude of forms. The deposits can be classified in a number of ways; we present the following classification (with some examples given) mainly to show the great range and complexity of deposit types; the classification will facilitate our descriptions of individual deposits and evaluations of deposit types in later parts of this report.

A. Volcanic rock associations

1. Veins (Wagon Wheel Gap, Colo.)
2. Mantos (Sierra Cuchillo, N. Mex.)
3. Pipes (Thomas Range, Utah)
4. Disseminated deposits (Thomas Range, Utah)
5. Tuffaceous lake beds (Rome, Oreg.)
6. Volcanic necks and diatremes (Hicks Dome, Ill.)

B. Intrusive rock associations

1. Breccia stockworks (Jamestown, Colo.)
2. Pipes (southeast Alaska)
3. Veins (York Mountains, Alaska)
4. Contact zones, including tactites (Iron Mountain, N. Mex.)
5. Disseminated deposits (topaz and fluorite at Climax, Colo.)
6. Pegmatites (Petaca district, New Mexico; Darby, Mont.)
7. Fluorine-rich syenites and granites (Pikes Peak Granite, Colorado)
8. Greisens (Lake George, Colo.)

C. Metamorphic rock associations

1. Layered gneisses (topaz at Evergreen, Colo.)
2. Fluorine-bearing marbles (McAfee, N.J.)
3. Contact metamorphic deposits with magnetite-franklinite-fluorite-apatite (northern New York and northwestern New Jersey)
4. Contact metamorphic deposits with humite (Brewster, N.Y.)

D. Sedimentary rock associations

1. Phosphate rock (Phosphoria Formation, Western United States)
2. Veins, breccia pipes, or mantos in carbonate rock, shale, or sandstone (Illinois-Kentucky district)

D. Sedimentary rock associations—Continued

3. Disseminations and vug fillings in carbonate rock (Permian of north-central Wyoming; Lockport, N. Y.)
4. Disseminated deposits in volcanoclastic rock (Thomas Range, Utah)
5. Tuffaceous lake beds (Rome, Oreg.)
6. Saline beds and basin brines (Searles Lake, Calif.)

E. Miscellaneous

1. Major fault zones with fluorite (Illinois-Kentucky district)
2. Cryptovolcanic structures (Hicks Dome, Ill.)

Some inevitable overlaps occur in this, or any other, classification. Therefore, we discuss the occurrence and distribution of deposits according to their primary mineral character (fluorite, topaz, or phosphate) and we discuss the geology of deposits and districts geographically, State by State.

FLUORINE IN FLUORITE DEPOSITS AND OCCURRENCES

Fluorspar is a mineral aggregate or mass containing enough fluorite (CaF_2) to be of commercial interest; pure fluorite is 51.1 percent calcium and 48.9 percent fluorine. Fluorite is harder than calcite (CaCO_3) and softer than quartz (SiO_2), two common mineral associates with which it may be confused, and is appreciably heavier than either one; it is not as heavy as barite, another common associate. Fluorite has a vitreous luster and a wide variety of colors, commonly shades of purple or green, but also white to yellow, green, blue, rose, purple, red, brown and purplish black. Fluorite generally crystallizes as cubes or octahedrons but may occur in massive form, crusts, globular aggregates showing radial fibrous textures, and earthy and banded cryptocrystalline forms resembling chalcedony. It has perfect octahedral cleavage, which with its characteristic crystal forms, color, heaviness, and hardness generally is sufficient to differentiate it from other minerals. Minerals other than calcite and quartz commonly found in fluorspar deposits are barite (BaSO_4), galena (PbS), sphalerite (ZnS), pyrite (FeS_2), chalcocite (Cu_2S), hematite (Fe_2O_3), limonite (hydrated ferric oxide), manganese oxides, clay, and various oxidation products from breakdown of the sulfide minerals. In a few deposits the fluorite is accompanied by uranium, rare-earth, or beryllium minerals, where they locally might be coproducts; major fluorspar districts with associated uranium minerals include Jamestown, Colo., Thomas Range, Utah, and Bare Mountain, Nev. (Wilmarth and others, 1952).

Fluorine is widely distributed throughout the United States in fluorite deposits (fig. 9). The patterned areas of figure 9 include reported occurrences of fluorite as well as productive fluorspar deposits. Generally speaking, most

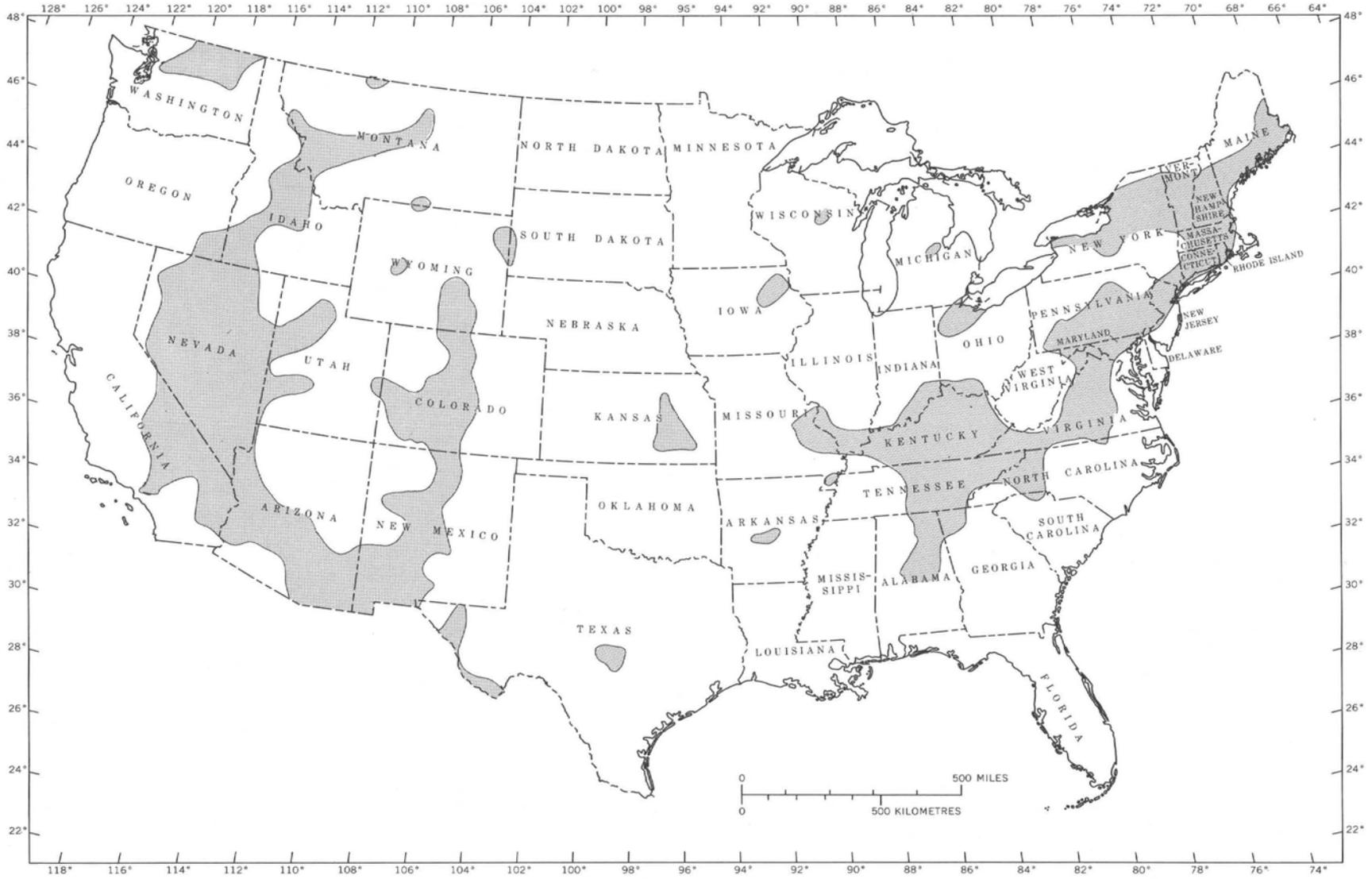


FIGURE 9.—Distribution of fluorite deposits in the United States, based on Worl, Van Alstine, and Heyl (1974).

of the fluor spar deposits and fluorite occurrences are found in the mountainous regions of the Western United States excluding the Colorado Plateau, and in the Appalachian Mountains in the Eastern United States. The principal producing area of the United States—the Illinois-Kentucky district—is outside of mountainous regions.

FLUORINE IN TOPAZ DEPOSITS AND OCCURRENCES

Topaz ($\text{Al}_2 [\text{SiO}_4] (\text{OH}, \text{F})_2$) generally has not been produced as a commercial source of fluorine although the fluorine content of topaz is high enough to suggest a potential source. Topaz ideally contains 32.6 percent silica, 55.4 percent alumina, and 20.7 percent fluorine (total 108.7 percent, less 8.7 percent O for F). Topaz is hard (harder than quartz and softer than corundum) and heavy (density 3.49–3.57). Color is variable, commonly colorless to yellow, pink, light blue, and light green. Its hardness and vitreous luster have made colored topaz a valuable gem mineral. Topaz usually forms orthorhombic prisms with perfect basal cleavage. Common mineral associates are quartz, fluorite, tourmaline, beryl, cassiterite, wolframite, rutile, and muscovite.

Topaz is found chiefly in silicic igneous rocks such as granites, granite pegmatites, and rhyolites and in veins, disseminated deposits, and greisens associated with these. It is also associated with other heavy minerals in placers near certain silicic intrusive rocks.

Topaz deposits are widely distributed throughout the United States, as shown in figure 10.

FLUORINE IN PHOSPHATE AND FLUORAPATITE DEPOSITS

Fluorine-bearing phosphate deposits occur in rocks of all geologic eras from Precambrian to Cenozoic as igneous apatite, sedimentary phosphorite, and guano deposits, and as secondary accumulations formed by weathering, diagenesis, and reworking of any of the primary materials. Fluorine is present in economically interesting amounts in phosphate deposits in many parts of the United States, and in particularly large amounts in sedimentary phosphorite deposits. The phosphate mineral of the sedimentary phosphorite deposits is carbonate fluorapatite— $\text{Ca}_{10}(\text{PO}_4, \text{CO}_3)_6\text{F}_{2-3}$. The ratio of F to P_2O_5 in this mineral is about 1 to 10; P_2O_5 content in minable deposits ranges from 28 to 38 percent, and F content of mined phosphate of the Phosphoria Formation in the Western United States is about 3.1 percent, that of Eastern phosphates is 3.6–3.8 percent. Presently commercial phosphate deposits in which fluorine occurs as a potential by-product are confined to marine sedimentary phosphorites of Ordovician age in Tennessee, of Permian age in the Western United States (southwestern Montana, southeastern Idaho, western Wyoming, and northern Utah), of

Miocene age in North Carolina, Georgia, and South Carolina, and of Miocene and Pliocene ages in Florida, and to residual deposits derived from some of them. Locations of phosphate deposits in the United States are shown in figure 11.

The phosphate deposits of the Atlantic Coastal Plain (Florida, Georgia, South Carolina, and North Carolina) are in unconsolidated rocks of Tertiary age. The deposits consist of quartz sand, clay, and irregularly rounded, highly polished, generally dark colored phosphate grains. The phosphate grains range in size from about 0.1 mm to several centimetres in diameter, but most are sand sized.

The phosphate deposits of Tennessee are derived from calcareous rocks of Ordovician age. The deposits are residual and consist of rounded grains of sand- to silt-sized brown phosphate, quartz, and minor clay. Irregular masses of quartz and phosphate sand cemented by phosphate are common.

The phosphate deposits of the Western United States (Idaho, Montana, Wyoming, and Utah) are in rocks of the Phosphoria Formation of Permian age. The deposits consist of consolidated beds of carbonaceous, pelletal, sandy phosphorite associated with black shale, chert, and limestone.

Nonsedimentary fluorapatite deposits of a variety of types may have potential for byproduct fluorine production (fig. 11). Fluorapatite occurs with magnetite at Ausable, Mineville, and Trembley Mountain, N.Y.; Canfield mine, Dover, N.J., and Iron Mountain, Mo.; with rare-earth fluocarboxylates and magnetite at Scrub Oaks mine, Dover, N.J.; in skarn in Hurdstown, N.J.; and in dikes with ilmenite near Roseland and Piney River, Va. Fluorapatite is found in magnetite-rich contact metamorphic deposits at Iron Springs, Utah, and at the Barth mine, the Modarelli mine, the McCoy district, the Black Joe prospect, the Emery-Fisk prospect, and in the Buena Vista Hills, Nev.

FLUORINE IN OTHER DEPOSITS

Fluorite, topaz, and fluorapatite occur also in types of deposits other than those just described. In addition, some other fluorine-bearing minerals of possible economic significance are the fluorides, cryolite, Na_3AlF_6 , sellaite, MgF_2 , and villiumite, NaF ; the humite group of fluorine hydroxysilicates; and bastnaesite, $(\text{Ce}, \text{La})(\text{CO}_3)\text{F}$, whereas other still less common fluorine-bearing minerals will probably be of little economic significance in the future. Fluorine is also present in many other minerals including silicates like tourmaline and the micas (phlogopite, zinnwaldite, lepidolite, muscovite, and biotite), and phosphates (monazite, xenotime, and amblygonite).

Some types of deposits are not known domestically.

A cryolite deposit at Ivigtut, Greenland, is virtually a monomineralic pegmatite although it contains also some complex fluorides, fluorite, topaz, microcline, columbite,



FIGURE 10.—Locations of major topaz deposits, topaz occurrences, and topaz-bearing rhyolites in the United States.

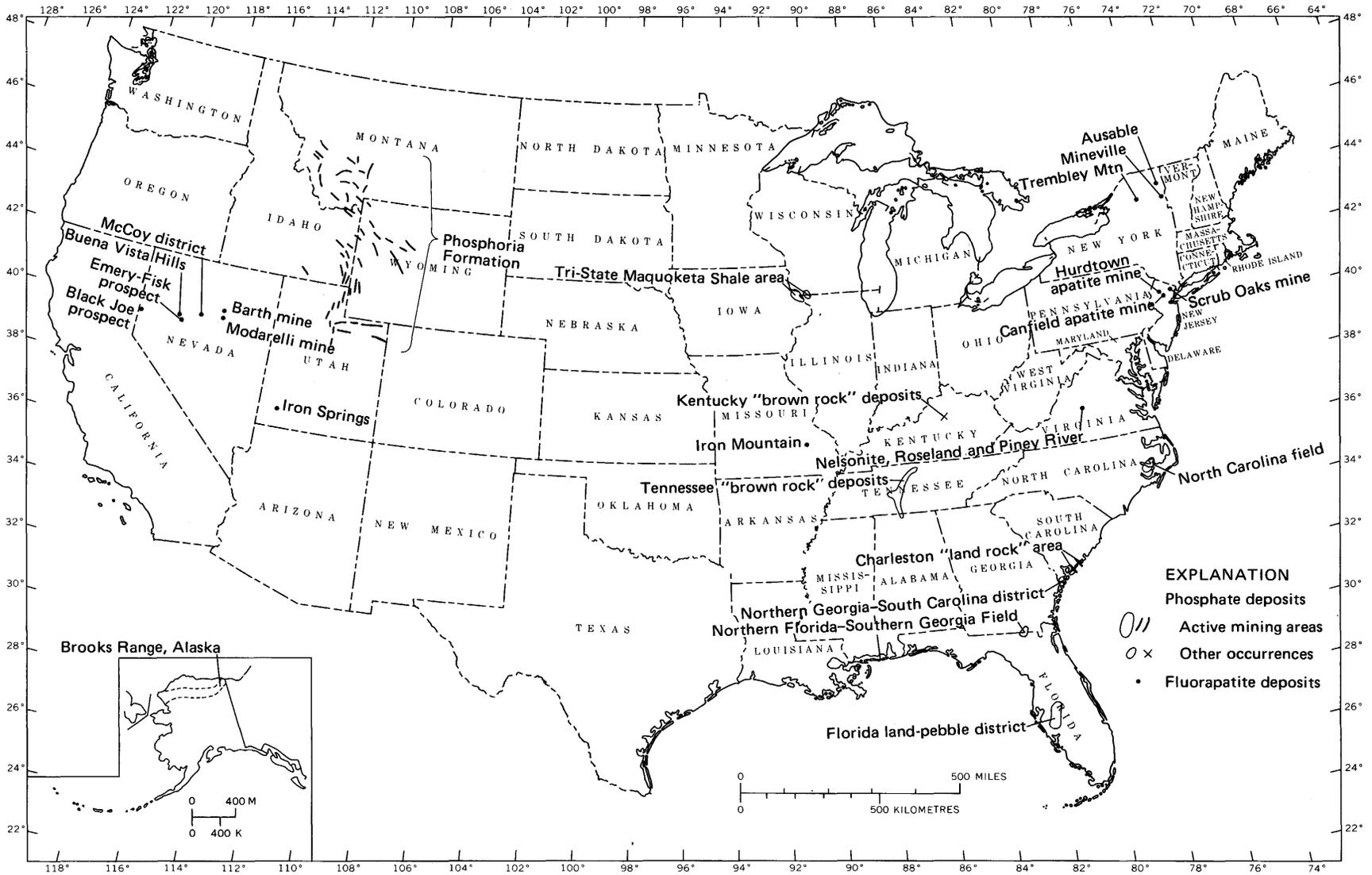


FIGURE 11.—Locations of phosphate rock and other fluorapatite deposits in the United States.

siderite, pyrite, sphalerite, galena, and chalcocopyrite. The pegmatite lies within porphyritic granite intrusive into gneiss. The deposit, mined out in 1963 after about 100 years of production, yielded about 17,000 metric tons of cryolite annually prior to 1930 (Lindgren, 1933a, p. 765), averaged almost 30,000 metric tons annually during 1935-38 and more than 50,000 metric tons annually during 1940-44 (Mudd, 1949, p. 401). It produced about 50,000 metric tons between 1949 and 1956 (Grogan, 1960, p. 381).

Some lacustrine brines and evaporites contain concentrations of fluorine; the best examples are the brines and recent evaporites of lakes in the rift valleys of Africa where lake waters contain as much as 1,625 ppm F. The evaporite sequence of Lake Magadi, Kenya, composed largely of trona, locally contains as much as 22 percent villiamite, and fluorite is common throughout much of the sequence (Sheppard and Gude, 1969, p. D73).

Fluorite is common in the belt of Lower Carboniferous limestones and dolomites at the southwest margin of the Donets basin, U.S.S.R., occurring generally as fracture fillings in siliceous limestones (Panov, 1962). The fluorite is thought to be diagenetic and associated in origin with some of the carbonates. The fluorite occurs as cubes associated with quartz and pyrite crystals. It is mostly dark purple or pinkish, and some is pale violet, green, colorless, or black. Also, Abramovich and Nechayev (1960) noted possible economic concentrations of fluorine in Permian marine carbonates and evaporites west of the Urals in the U.S.S.R. Fluorite occurs as a fine dissemination and as crystalline aggregates in vugs in dolomitized limestone. The CaF_2 content of some zones exceeds 30 percent. Kazakov and Sokolova (1950) noted that fluorite in marine carbonates of the U.S.S.R. is related to the saline facies of relict basins, mainly to dolomite, dolomitized limestones, phosphate, gypsum, redrocks, anhydrite, potassium and magnesium salts, and celestite.

A minor occurrence in Permian dolomitic limestones of Wyoming contains 12-15 percent CaF_2 .

Carbonatite complexes are notably enriched in fluorine mostly dispersed through the rock in silicates, apatite, and bastnaesite. Deposits at Okorusu, South-West Africa, and at Amba Dongar, India, are economic fluorine deposits consisting of fluorite-bearing contact zones and late-stage hydrothermal veins (Deans and others, 1972). Apatite-bearing carbonatite—the principal source of phosphate in southern and eastern Africa—contains 1-3 percent fluorine, and considerable reserves are known (Deans, 1966, p. 393). Apatite-bearing carbonatite rock near Jacupiranga, Sao Paulo, Brazil, being mined for phosphate, contains 4-5 percent fluorine (Abreu, 1960, p. 123), and apatite-bearing carbonatite rocks in the U.S.S.R. are a present source of fluorine, recovered as a byproduct of fertilizer production. Carbonatite at Mountain Pass, Calif., contains at least 1 percent fluorine, mostly in bastnaesite (Olson and others, 1954); about 1,000,000 tons

of fluorine exists as a potential byproduct of rare-earth extraction at Mountain Pass.

Fluorspar deposits in unconsolidated tuffs near Rome, Italy, are lenses composed of finely crystalline fluorite, barite, calcite, dolomite, apatite, opal, and chalcedonic quartz with minor amounts of detrital minerals and volcanic glass. Fluorite content of some zones averages 55 percent. These lenses are thought to be chemical sedimentary deposits formed in lake basins by hydrothermal fluids rich in fluorine, calcium, barium, strontium, silicon, sulfur, and phosphorus (Spada, 1969).

TECTONIC SETTING OF FLUORINE DEPOSITS

By D. R. SHAW

Distribution of fluorine mineral deposits in the United States has been strongly controlled by tectonic environment. Regions containing fluorine mineral deposits are geologic provinces generally characterized by many faults and intrusive igneous rocks. This generalization applies to virtually all types of fluorine occurrences, with the notable exception of those deposits formed during sedimentation, particularly the sedimentary phosphate deposits. Some geophysical parameters broadly reflect the tectonic composition of the United States and thus outline regions of known or expected fluorine deposits.

RELATION OF FLUORINE DEPOSITS TO FAULTS

Areas of fluorine mineral deposits are near major faults in the United States (fig. 12). Faults in figure 12 are somewhat generalized and some of them represent major zones of faults.

Practically all fluorspar deposits—the dominant type of epigenetic fluorine mineral deposits—are closely associated with faults, especially in areas of tension along the margins of uplifts or structural basins (Van Alstine, 1954). Many deposits occur as veins along faults or as replacement deposits in fractured rocks close to faults. The dominant orientations of regional faults that have controlled fluorspar deposits are northwesterly, north-easterly, and easterly.

Fluorspar deposits are associated with both strike-slip faults and tensional, normal faults such as the north-trending faults in the Basin-Range province of the Western United States. Indeed, the distribution of fluorine mineral deposits in the Western United States closely follows that of Basin-Range structure (fig. 13). For example, the Rio Grande trough in New Mexico and its projection northward through Colorado has localized fluorspar deposits. Also, in southwestern New Mexico, fluorspar deposits in places occur in Basin-Range faults (Elston, 1970, p. 147, 150). On the other hand, fluorspar deposits in the Eastern United States are related generally to zones of strike-slip, not tensional, faults.

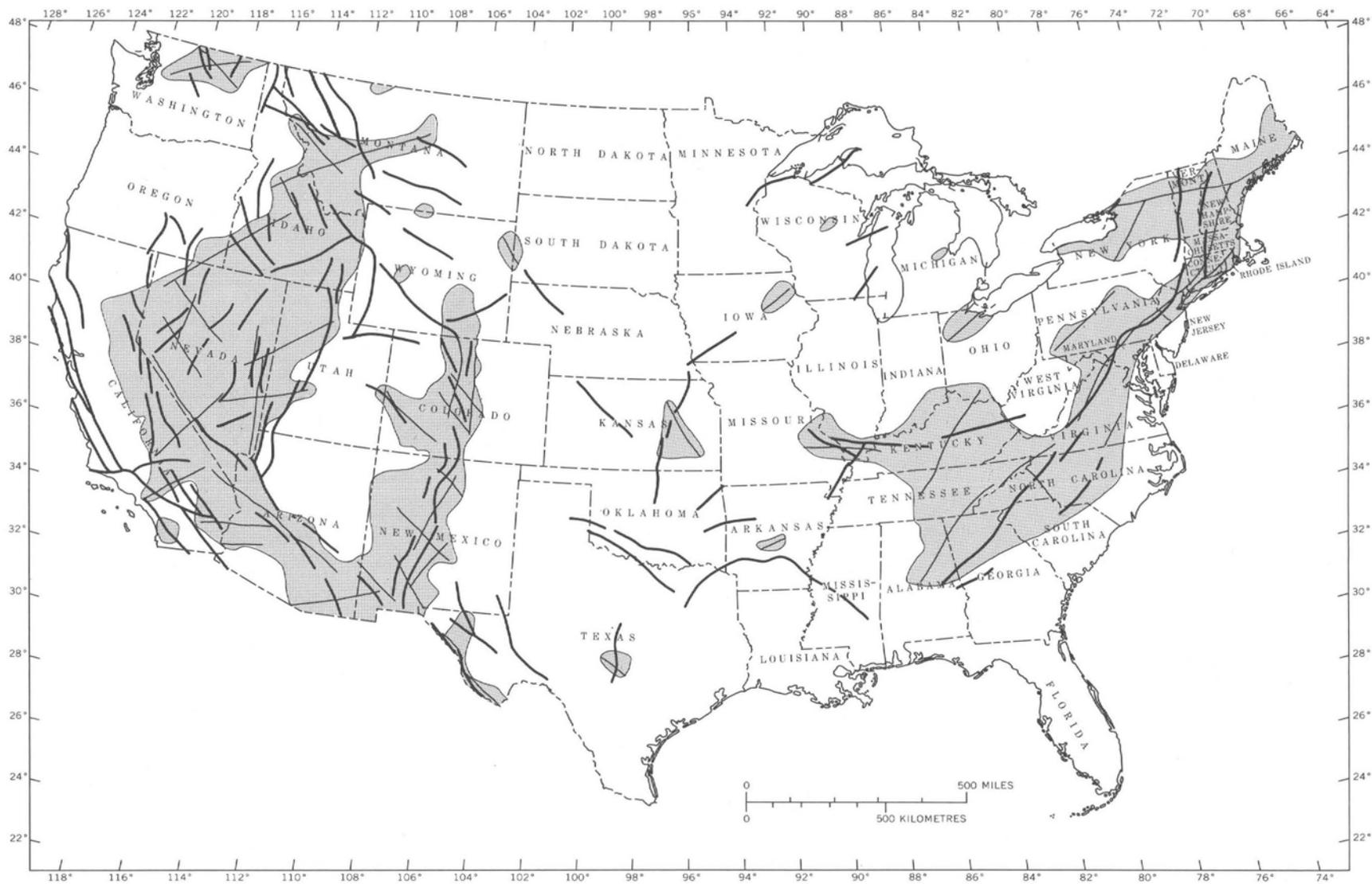


FIGURE 12.—Major faults (heavy lines) and distribution of fluorine minerals (shaded) in the United States: fluorite, topaz, and fluorapatite (excluding sedimentary phosphorite). Thin lines are alignments of major elongate clusters (belts) of fluorite deposits.

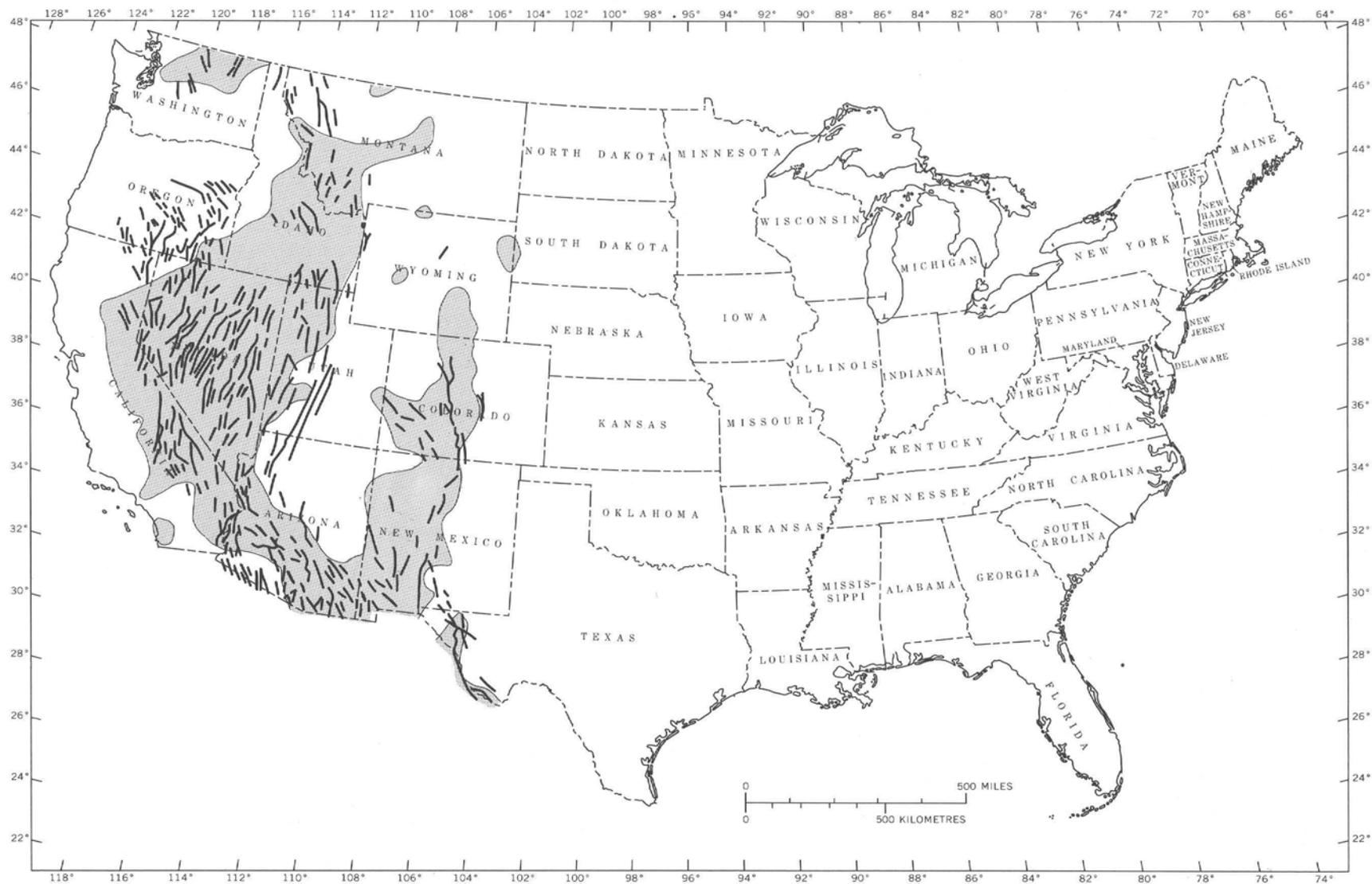


FIGURE 13.—Normal faults (heavy lines; after Gilluly, 1963, and other sources), and distribution (shaded) of fluorine mineral deposits in the Western United States.

Figure 12 shows that a number of major faults have no known fluorine mineral deposits associated with them, for example the San Andreas strike-slip fault zone along the Pacific Coast of California.

Fluorspar deposits tend to occur in elongate clusters that form aligned zones or belts (fig. 12; Worl, Van Alstine, and Heyl, 1974). Northwesterly and northeasterly alignments dominate. Some northerly alignments are evident in Nevada and Colorado and some easterly alignments show up in southern Arizona, in the Missouri-Illinois-Kentucky area, and in the northeastern United States. In places the alignments of fluorspar deposits nearly coincide with major faults even though individual deposits may not actually occur in the major faults themselves.

In the Eastern United States dominant northeasterly alignments of fluorspar belts reflect the dominant northeasterly structural grain of the region.

In the Western United States in the Basin-Range province, however, fluorspar belts align northwesterly and northeasterly but structural grain aligns northerly. Some pre-Basin-Range faults are oriented northwesterly and northeasterly, have been deformed by strike-slip movement (for example, Shawe, 1965, p. 1372-1375), and are reflected by alignment of the fluorspar belts.

RELATION OF FLUORINE DEPOSITS TO INTRUSIVE IGNEOUS ROCKS

The general coincidence of epigenetic fluorine mineral deposits and intrusive rocks in the United States is shown in figure 14. In some large areas in which fluorine deposits occur no intrusive rocks are shown in the figure; numerous intrusives are known in these areas but are too small to be shown at the scale of the map. For example, many small mafic intrusives rocks are present in the Illinois-Kentucky district; intrusives are present at Magnet Cove, central Arkansas; and Precambrian intrusives (not depicted in fig. 14) have numerous associated fluorine mineral occurrences in central Texas and in central Colorado.

On the basis of rather incomplete data the ages of the fluorine mineral deposits correlate with the ages of the intrusive rocks with which they are associated. Fluorite- and topaz-bearing greisens and pegmatites were formed during the igneous cycle of the Pikes Peak Granite of central Colorado and of the granite in the Llano uplift of central Texas, both of Precambrian Y age (800-1,600 m.y.—million years). The ages of fluorine-bearing greisens and pegmatites agree with those of their associated Paleozoic granitic rocks in the Eastern United States (fig. 14). Skarn or contact metamorphic deposits containing fluorine-bearing minerals are clearly associated with specific plutons of Paleozoic age in the Eastern United States and of Mesozoic and Cenozoic age in the Western United States. These deposits were formed either at the time of emplacement of the plutons or shortly

thereafter as a late stage phenomenon of the igneous episode, and hence are certainly of nearly the same age as the intrusive rocks. Many fluorine mineral deposits in the Western United States in Tertiary volcanic rocks or near Tertiary intrusive rocks can be dated by geologic relations as Tertiary in age (R. G. Worl, written commun., 1972). The dated deposits are all younger than 32 m.y. and none of these are demonstrably younger than 6 m.y., with the exception of a few hot-springs apron deposits such as that at Ojo Caliente, N. Mex., that currently are being deposited.

The age distribution of these 6-32 m.y. (Tertiary) deposits does not coincide, however, with the age distribution of the times of transition from andesitic to fundamentally basaltic volcanism in the Western United States shown by Christiansen and Lipman (1972, fig. 5). Their data suggest successively younger ages from western Texas northward and westward, but Worl (written commun., 1973) shows fluorspar deposits of widely differing ages randomly distributed in the Western United States. The deposits thus clearly are not related to the beginning of the episode of basaltic-rhyolitic (bimodal) volcanism, but may have formed locally any time thereafter. In fact, some fluorspar deposits are related to alkalic rocks formed during earlier predominantly andesitic volcanism.

Strong evidence suggests that Tertiary deposits are related genetically in some places to inferred intrusive rocks even though the deposits are associated spatially with extrusive rocks. At Spor Mountain, Utah, for example, Staatz and Osterwald (1959, p. 59-61) demonstrated the likelihood of fluorine-rich intrusives at depth, similar in composition to the widespread topaz-bearing rhyolites at the surface near Spor Mountain, and showed that such intrusives were the likely sources of the fluorine in the fluorspar deposits.

At Climax, Colo., fluorite and topaz were deposited with molybdenite in several successive episodes each related to intrusion of an alkalic-silicic porphyry stock of middle Tertiary age (Wallace and others, 1968).

Fluorine-rich igneous rocks form two well-defined provinces—one in the Eastern United States and one in the Western United States (fig. 8)—that roughly accord with areas of intrusive rocks outlined on figure 14, but there are important variations in the distributions. For example, Tertiary intrusive rocks are distributed in a broad belt through the Western United States, but they are enriched in fluorine only in parts of the broad belt, and these parts generally coincide with areas of fluorine mineral deposits. The absence of fluorine-rich rocks in north-central Washington State shown in figure 8, despite the presence of fluorine mineral deposits (fig. 14), is thought to reflect lack of data rather than a real absence of such rocks in the area. The striking coincidence overall of the areas of fluorine-rich igneous rocks with areas of epigenetic fluorine mineral deposits (compare fig. 8 with fig. 14)

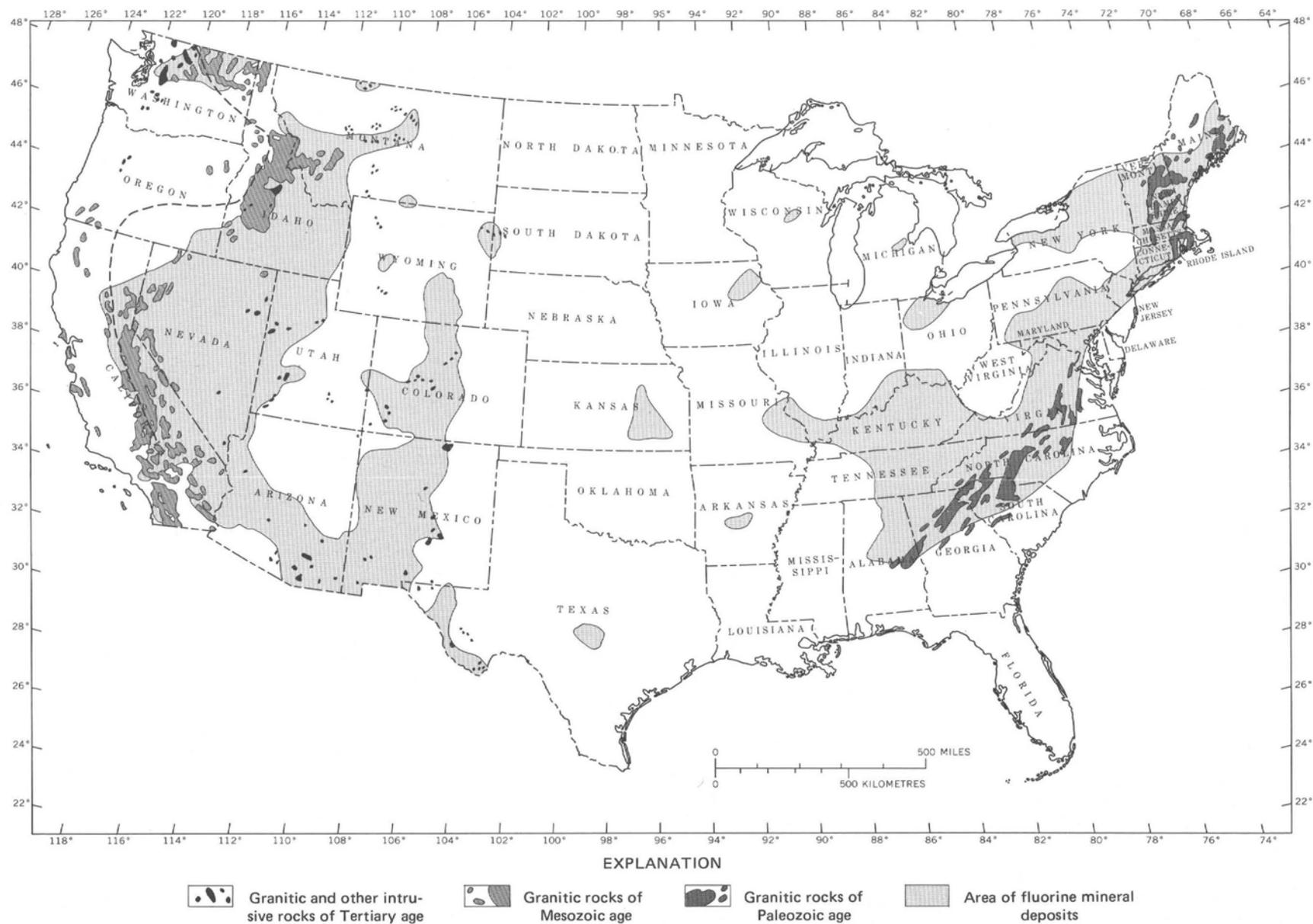


FIGURE 14.—Major Phanerozoic intrusive bodies (from King, 1967) and distribution of epigenetic fluorine minerals in the United States.

indicates a likely genetic relation between such igneous rocks and mineral deposits. In a number of places fluorine-rich igneous rocks are related genetically to the associated fluorine mineral deposits. This is true of the Pikes Peak Granite, Colorado, and associated topaz and greisen fluorspar deposits; the granite of the Llano uplift, Texas, and associated fluorine mineral deposits; a number of plutons in the Eastern United States and their associated greisen and pegmatite deposits; tin granites and associated fluorspar deposits at Lost River, Alaska; and the Climax, Colo., stocks and associated topaz- and fluorite-bearing molybdenite deposits. In other places well-based inference suggests a genetic relation, as in the Illinois-Kentucky district where fluorspar is spatially associated with fluorine-rich mafic alkalic rocks, at Magnet Cove, Ark., where fluorspar is spatially associated with fluorine-rich alkalic rocks, and at Spor Mountain, Utah, and the southern Wah Wah Mountains, Utah, where fluorspar deposits are spatially associated with topaz-bearing rhyolites and their inferred intrusive equivalents.

The tendency for intrusive rocks of special chemical composition to correlate with fluorine mineral deposits is illustrated in another way. The quartz diorite line of Moore (1959), which marks the western margin of potassium-enriched intrusive rocks in the Western United States (fig. 14), forms an approximate western boundary of the areas of fluorine mineral deposits. Perhaps the higher potassium content of intrusive rocks east of the quartz diorite line correlates partly with a higher fluorine content of the rocks in this region.

RELATION OF FLUORINE DEPOSITS TO GEOPHYSICAL PROPERTIES

Figure 15 shows Bouguer gravity data for the United States in relation to the distribution of fluorine mineral deposits. Low-gravity regions, highlighted on the map, in a general way represent zones in the lithosphere—in the crust and possibly also in the upper mantle—where rocks are more silicic and hence lighter than in surrounding areas. These regions broadly represent crustal zones intruded by significant volumes of silicic igneous rocks. The low-gravity contours also roughly outline topographically high regions—the mountainous parts of the country—that have risen isostatically in response to their low density. These low-gravity regions roughly correlate with areas of fluorine mineral deposits, but the correlation is imperfect or lacking in wide areas. Most significant is the absence of a low-gravity zone in the vicinity of the important Illinois-Kentucky fluorspar district. On the other hand, an area of fluorine deposits in north-central Washington State nearly coincides with a low-gravity zone; west- and east-trending lobes of fluorine mineral occurrences in western and central Montana coincide with similarly trending low-gravity lobes; the important zone of fluorine mineral deposits extending northward

through central Colorado nearly coincides with a major gravity low; a string of fluorine mineral occurrences extending from eastern Kansas northeastward through Wisconsin lies along a northeasterly oriented gravity low; and fluorine mineral occurrences in northwestern Ohio are clustered on a gravity low.

Moore (1962) suggested a correlation between high potassium content of Cenozoic igneous rocks and low Bouguer gravity values in the Western United States.

Heat-flow values in the Western United States reported by Blackwell (1971, fig. 2) are relatively high and generally exceed 2×10^{-6} cal/cm²/sec in broad regions that coincide remarkably with the distribution of fluorite deposits in this part of the country (fig. 16). Comparison of figure 16 with figure 8 also shows a striking coincidence in the distribution of high heat-flow values and the distribution of fluorine-rich igneous rocks in the Western United States. (Again, if fluorine-rich rocks are present in northern Washington, a condition unknown for lack of data, the correlation would be improved.) On the other hand, comparison of the heat-flow data with the distribution of Tertiary intrusive rocks in the Western United States (fig. 14) shows a generally poor correlation; numerous Tertiary intrusives occur in western Oregon and Washington, in central Montana, in western Wyoming, and in southeastern Utah where heat-flow values appear to be low and no fluorine mineral deposits are known.

Present heat flow (fig. 16) may be different from that in the middle to late Tertiary when fluorine mineral deposits and fluorine-rich igneous rocks were forming. However, some of the fluorine-rich volcanic rocks are as young as 3 m.y. (Armstrong, 1970, table 3, p. 210–211), and the occurrence of fluorite in modern hot-springs aprons at Ojo Caliente, N. Mex., and elsewhere, indicates that the episode of fluorine mobility likely extends from the Tertiary into the Holocene. Probably the episode of fluorine-rich magmatism and fluorine mineral deposition that commenced about 30 m.y. ago (middle Tertiary) in the Western United States is still manifested by high heat flow throughout the region of that magmatism and mineralization.

Where regional aeromagnetic data are available, some correlations between magnetic anomalies and the distribution of fluorite deposits are apparent. For example, in Colorado the positions of elongate zones (alignments) of numerous sharp positive aeromagnetic anomalies (Zietz and Kirby, 1972) nearly coincide with the positions of fluorite mineral belts (fig. 16) and are inferred to represent in part zones of buried intrusive rocks.

On a global scale, residual magnetic contours based on data taken by U.S.S.R. satellite Cosmos 49 at altitudes of 155–310 miles (250–500 km) (Zietz and others, 1970, fig. 3) show pronounced northeasterly and northwesterly orientations across much of the United States, reflecting

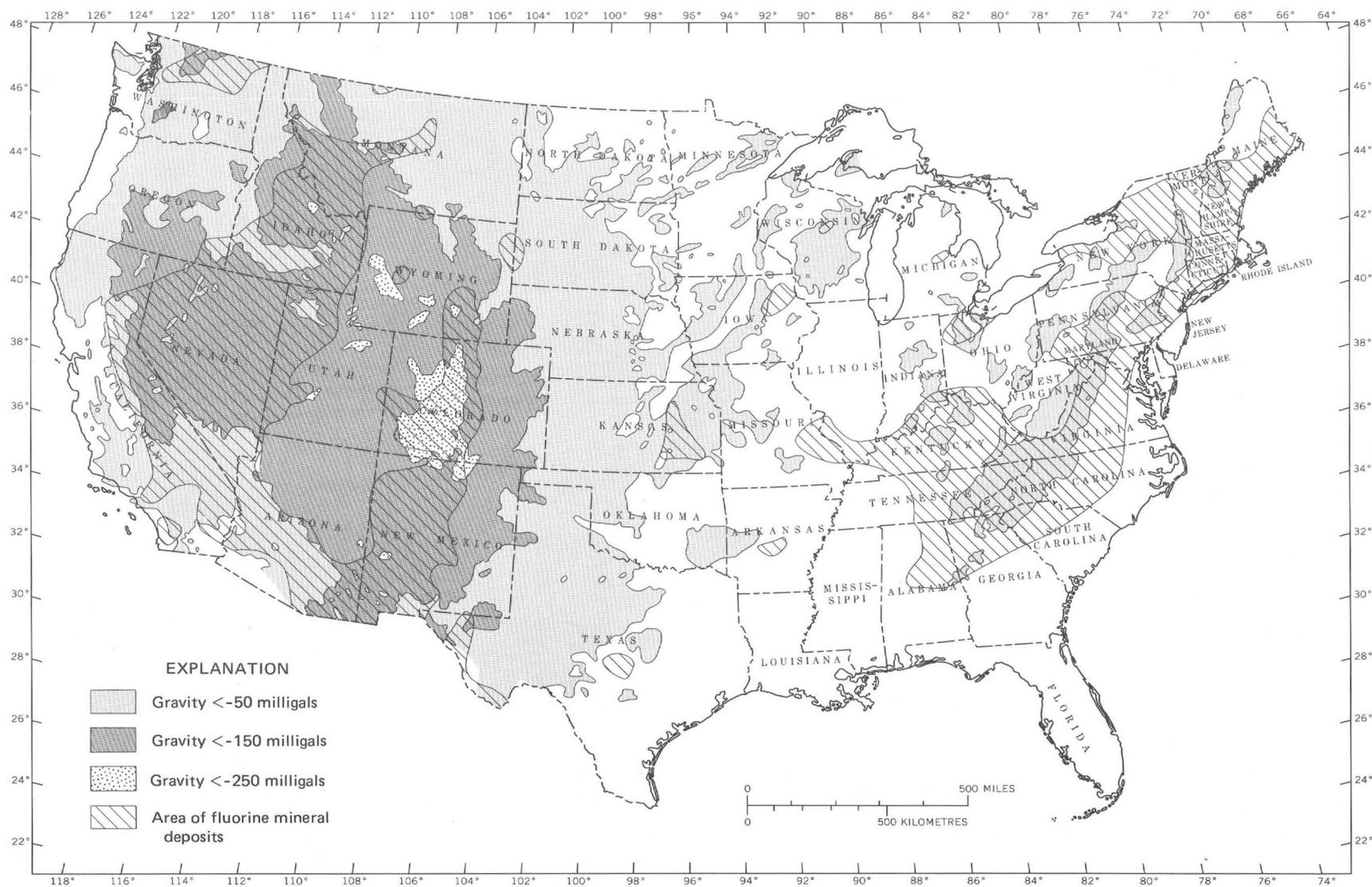
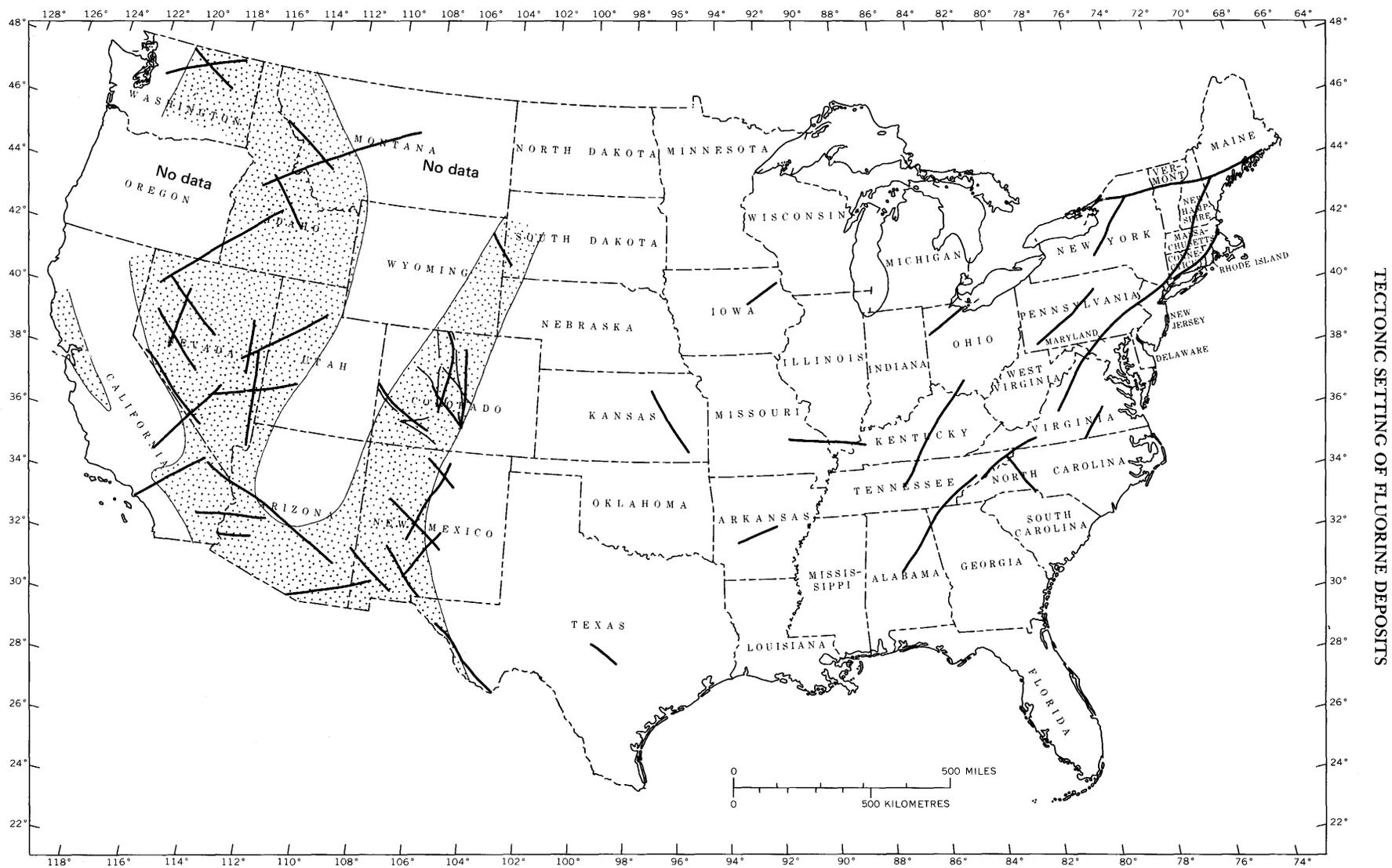


FIGURE 15.—Bouguer gravity (after Woollard and Joesting, 1964) and distribution of fluorine mineral deposits in the United States.



TECTONIC SETTING OF FLUORINE DEPOSITS

FIGURE 16.—Fluorite mineral belts (heavy lines) and regions (stippled) in the Western United States with heat-flow values generally greater than 2.0×10^{-6} cal/cm²/sec (based on Blackwell, 1971, fig. 2). Thin lines in Colorado show alignments of numerous sharp positive aeromagnetic anomalies (based on Zietz and Kirby, 1972) that in part may represent zones of buried intrusive rocks.

the dominance of these directions in gross crustal structure.

Earthquake epicenters in the United States reported through 1964 and shown by Woollard (1969, fig. 1) are characteristically disposed in elongate clusters that trend dominantly northeasterly and northwesterly. The earthquakes undoubtedly are related to zones of active faulting which reflect a fundamental structural framework of the continent. Some of the northeasterly and northwesterly zones of seismic activity coincide with fluorite mineral belts, substantiating the conclusion that the mineral belts are in part related to major fault zones. The fault zones no doubt are of considerable age and some must reflect part of the Precambrian as well as Phanerozoic structural grain.

Crustal thickness and mean crustal seismic velocity show little relation to the distribution of fluorine mineral deposits (fig. 17). For example, crustal thickness varies from more than 30 miles (50 km) to less than 20 miles (30 km) in less than 60 miles (100 km) horizontally within the fluorine province in eastern California and western Nevada, and crustal thickness ranges from slightly more than 30 miles (50 km) to less than 20 miles (30 km) from Colorado through New Mexico and into southern Arizona without commensurate change in the general character of fluorine mineral deposits in these regions. Mean crustal seismic velocity, which reflects primarily crustal composition and to a lesser degree structural complexity, also shows no correlation with the distribution of fluorine mineral deposits. Apparently the formation of fluorine deposits is not closely related to any crustal properties that influence crustal thickness and seismic velocity.

A broad region of low (<8 km/sec) upper-mantle seismic velocity is present in the Western United States and this region quite closely encompasses the region of middle to late Tertiary volcanism and fluorine mineralization (fig. 17). The region of low velocity in the upper mantle likely is characterized by above-normal temperatures, and this condition generally accords with the high heat flow of the overlying crust (fig. 15). Woollard (1968) proposed that the region of low seismic velocity in the upper mantle may reflect a phase transition from normal mantle material of dunite composition, high seismic velocity, and density ≈ 3.35 , into mantle material of eclogite composition, lower seismic velocity, and higher density. The compositional change resulting from the phase transition suggested by Woollard may have involved fractionation of materials from the upper mantle into the overlying crust, and this event may have taken place in the recent geologic past, from middle Tertiary time onward. Possibly these materials included high-fluorine basaltic and rhyolitic magmas and fluorine-rich fluids that penetrated upward toward the surface of the crust, to account for the fluorine-rich igneous rocks and fluorine mineral deposits of middle Tertiary and younger age in the province. On the other

hand, the magmatism and fluorine mineralization may have been phenomena originating within the crust, but in response to high heat flow from the mantle and to related processes. In any case, the spatial coincidence of the region of low upper-mantle velocity with a region of high heat flow, middle to late Tertiary fluorine-rich magmatism, and middle to late Tertiary fluorine mineralization indicates a strong mantle control on the magmatism and fluorine mineralization.

DESCRIPTIONS OF MAJOR FLUORINE DEPOSITS AND DISTRICTS AND IMPORTANT TYPES OF FLUORINE OCCURRENCES

Fluorine deposits are discussed in following pages in geographic groups characterized to some degree by common form, association, mineralogy, and geologic environment. Some deposits do not fit naturally into a classification based on geographic distribution but nevertheless are included in the geographic groups for convenience of discussion. The geographic divisions used are as follows: Alaska; Washington-Idaho-Montana-Wyoming-South Dakota; Nevada-Utah-southeastern California-western Arizona; Colorado-New Mexico-western Texas-southeastern Arizona; and Eastern and Central United States (including the Illinois-Kentucky district). Of course not all types of fluorine deposits are present in each geographic group. Within the geographic groups, deposits are described State by State where appropriate. Fluorine-bearing phosphate deposits of the conterminous United States are discussed as an additional group because of their unique character.

ALASKA

By C. L. SAINSBURY

Fluorine has not been produced commercially in Alaska, although fluorite is reported at many localities (Cobb, 1964; Worl, Van Alstine and Heyl, 1974). Topaz and fluorine-bearing phosphate rock are also known at several localities. The largest known deposits of fluorite—at Lost River, Seward Peninsula—were drilled extensively in 1972, and large reserves of fluorite (several million tons of contained CaF_2) associated with minerals of tin, tungsten, beryllium and base metals had already been announced (Northern Miner, Toronto, Oct. 1, 1970). These deposits are described in detail in this report; other deposits of smaller proved economic potential are described only briefly.

DESCRIPTIONS OF INDIVIDUAL DISTRICTS AND DEPOSITS

LOST RIVER

Fluorspar deposits at Lost River on the Seward Peninsula constitute the largest known fluorine potential in Alaska; the main deposits are located at lat 65°28' N.;

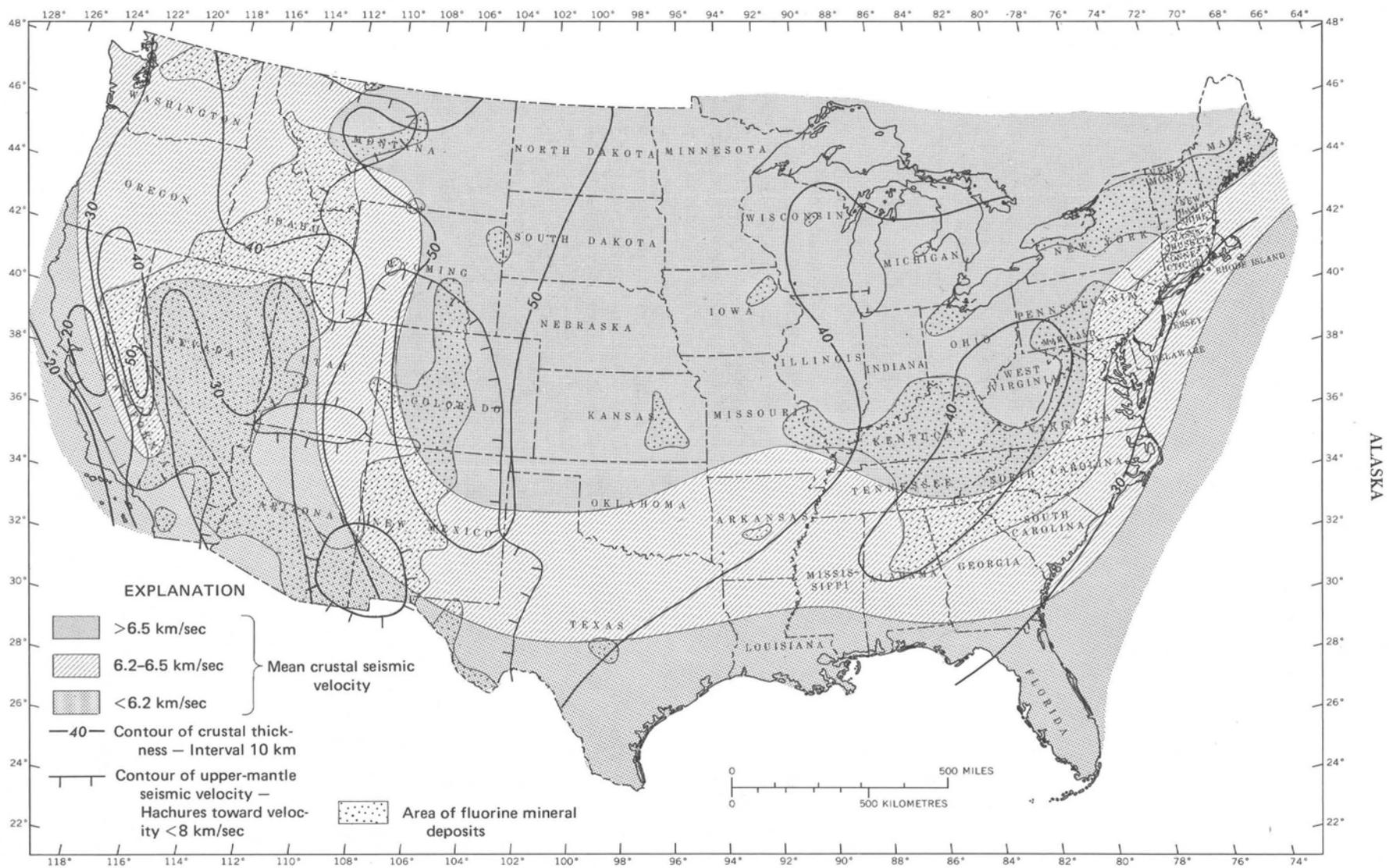


FIGURE 17.—Crustal thickness and mean crustal seismic velocity (from Pakiser and Zietz, 1965, fig. 2), upper-mantle seismic velocity (from Herrin and Taggart, 1962), and distribution of fluorine mineral deposits in the United States.

long 167°10' W. Although the main proved reserves are in and near the Lost River tin mine, other deposits of unassessed potential crop out discontinuously along the Rapid River thrust fault for a distance of several miles westward from the mine area.

Although the Lost River tin deposits were found in 1903, the beryllium-bearing fluorite lodes were found much later, in 1961–64, during a detailed geologic mapping program by the U.S. Geological Survey (Sainsbury, 1969).

No fluorite was produced during the mining of tin ores (1913–14 and 1949–55) from the Lost River mine, although much fluorite passed through the mill. Lost River has the potential of supplying a significant fraction of total United States fluorite production.

The main fluorite-bearing deposits in the Lost River area are almost entirely replacement bodies in limestone and argillaceous limestone of Early to Middle Ordovician age, which aggregate at least 8,000 feet (2,400 m), and possibly 12,000 feet (3,700 m) in thickness. The Lower Ordovician limestones are divided into two units, a lower shallow-water facies of thin-bedded argillaceous limestone with minor interbeds of thick-bedded limestone, possibly 4,500 feet (1,400 m) thick, and an upper quiet-water facies of medium- to thick-bedded limestone with interbeds of thin-bedded argillaceous limestone, about 6,500 feet (2,000 m) thick. Most of the known fluorite deposits are in rocks of these units although one deposit is within dolomitized limestone, below a thin black shale about 50 feet (15 m) thick, which is of early Middle Ordovician age. All these rocks are thrust-faulted in a major thrust province, and most ore bodies are localized in shattered dolomitized limestone and limestone beneath thrust faults, or in limestones near or above granite plutons.

Two main types of large deposits are known within the district, tin-poor stockworks and tin-rich stockworks. The larger (tin-poor) of these consists of replacement veins, veinlets, small pipes, and tabular replacement bodies in limestone and along the walls of lamprophyre dikes, all of which are localized near or within shattered rocks beneath thrust faults (for more detailed information on the several known deposits of this type see Sainsbury, 1969, p. 64–84). The principal tin-poor deposit (Camp Creek) adjoins the tin deposits at Lost River mine, and was explored by diamond-drill holes in 1964 by the U.S. Bureau of Mines (J. J. Mulligan, unpub. data, 1964; Mulligan presented some diamond-drill sampling data on the fluorite-beryllium deposits in the Lost River valley; Sainsbury, 1965), and by P.C.E. Explorations, Ltd., who proved an extension of the deposit by diamond drilling in 1970–72. This deposit extends for almost 4,000 feet (1,200 m) along the shattered zone beneath the Rapid River and Camp Creek thrust faults and raggedly downdip beneath the thrusts for several hundred feet. The deposit is best

classified as a stockwork which must be mined on a large scale with assay boundaries—ore reserves appear sufficient to satisfy a large-tonnage operation for several years (Northern Miner, Toronto, Oct. 1, 1970).

Beryllium is the most important associate of fluorite in the Camp Creek and similar deposits along the Rapid River fault, and tin is almost lacking. Four other areas, each several thousand feet long, contain stockworks of fluorite-beryllium veinlets and occur along the west extension of the Rapid River fault. The westernmost area, some 7 miles (11 km) west of Lost River mine, was drilled in 1962 by Newmont Mining Co.; this drilling showed that the mineralized zone dipped shallowly south beneath a small thrust which underlies the Rapid River fault. The mineralogy of the ores is similar to that of Camp Creek, described in the next paragraph, and tin-bearing sulfide ores were intersected in the deeper drill holes (Peter O. Sandvik, oral commun., 1963).

In the Camp Creek deposit, fluorite occurs as fine-grained intergrowths and interlayers with diaspore, tourmaline, white mica, and small amounts of the beryllium minerals chrysoberyl and euclase. The general mineralogy of the veins and veinlets in this type of deposit is as follows, in volume percent: fluorite, 45–65; diaspore, 5–15; tourmaline, 0–10; chrysoberyl, 3–10; white mica, 0–5; and small to variable amounts of todorokite¹, hematite and euclase, as well as trace amounts of phenakite, bertrandite, bityite and cassiterite. These ores typically are layered rhythmically on a scale of a millimetre or two, with finer layers of fluorite interlayered with fluorite that is accompanied by the minerals named above. The layering is parallel to the veinlets, and both veinlets and layers may cut obliquely across thin-bedded limestones without offsetting the bedding. Hence, the layers are interpreted as replacement “fronts.”

Studies of rocks and ores, as well as of individual minerals in the ores, reveal a common suite of trace elements such as tin, beryllium, silver, arsenic, lead, zinc, boron, lithium, and niobium, and show that the fluorite-beryllium deposits are distributed zonally above and around the tin deposits.

The second main type of deposit (tin-rich) is exemplified by the Lost River tin mine, which contains fluorite and topaz in close association with the tin ores, as well as in a large body of mineralized rock above a buried granite in the Cupola area (Sainsbury, 1964b). Fluorite-rich selvages along the tin ore shoot, which lies along an altered dike that dips steeply into the granite cupola, are as much as several feet thick, and contain both tin and beryllium minerals in addition to the fluorite. The Cupola area is a crudely conical mass of marmorized limestone cut both by garnet-bearing skarn bodies, and by an intricate

¹Work by Fred Hildebrand (written commun., 1970) showed that in addition to todorokite, pyrolusite and psilomelane occur in the ores, and that cryptomelane, chalcophanite, and birnesite may occur.

network of veins and veinlets containing fluorite, chrysoberyl, cassiterite, wolframite, topaz, quartz and numerous other minerals. Mining of this deposit, which contains several millions tons of material, would produce fluorite and several valuable byproducts. Ore reserves in the Cupola area (number 1 deposit of P.C.E. Explorations, Ltd.) amount to at least 5,974,000 tons of ore grading 30.80 percent CaF_2 , 0.30 percent tin, 0.18 percent BeO , and recoverable amounts of tungsten and base-metal sulfide (Northern Miner, Toronto Oct. 1, 1970).

Deposits which are transitional between tin lodes and beryllium lodes occur in Paleozoic limestone around the south side of the granite of Tin Creek, about 1 mile southeasterly from the Camp Creek beryllium lodes. These transitional deposits contain fluorite, chrysoberyl, cassiterite, manganese oxides, and sulfide minerals. Locally, high gold values have been reported in some of the oxidized sulfide veins (John Conrow, oral commun., 1963), a relation which was found to exist at the Rapid River beryllium-fluorite deposits (based on samples taken in 1970 by the Geological Survey). The ore minerals occur in numerous veinlets from a fraction of an inch to a few feet thick over an area of about one-half mile square; however, the area has not been drilled and the depth to granite is unknown. Hence, although the potential may be large, it is unassessed.

The distinguishing characteristics of the large fluorite deposits of the Lost River area are: (1) their association with tin deposits that are genetically related to biotite granites, (2) their complex mineralogy, which offers valuable byproducts as well as giving difficulty in beneficiation, and (3) their irregular form, which requires assays to determine their boundaries.

The structural location of ore bodies near or above biotite granite stocks, and the alignment of deposits along the Rapid River thrust fault, are notable. The great extent of mineralized rock along the Rapid River fault also is exceptional.

Studies of trace elements and fluid inclusions, and geologic mapping, show conclusively that the deposits are of hydrothermal origin, the fluorine, beryllium, boron, and other metallic elements being derived from deeper portions of the exposed granites in and around which the tin deposits are localized.

OTHER DEPOSITS

In addition to its occurrence in the main lodes near Lost River, fluorine occurs in fluorite, topaz or other fluorine-bearing minerals (idocrase, fluorine-micas) near other tin deposits on the Seward Peninsula, in breccia pipes cemented by fluorite in the Kigluaik Mountains, in scattered deposits of poorly assessed potential where alkalic rocks of Cretaceous age intrude carbonate rocks in the Darby Mountains, eastern Seward Peninsula, and in complex replacement bodies in interstratified marble and chloritic schist of Precambrian age north of Nome (Eakin,

1915; Brobst and others, 1971). Together, the deposits may delineate a fluorine-rich province genetically associated with silicic igneous intrusives of Cretaceous to Tertiary(?) age. Workers in this general area should at least be aware of the possibility of undiscovered commercial deposits of fluorspar.

Fluorite occurs in tin deposits near granite stocks at Cape Mountain, Brooks Mountain, Black Mountain, and Ear Mountain. None of these deposits is large enough to be of commercial significance. At Black Mountain, topaz is abundant in a small part of the granite that was greisenized. Similar greisenized granite at Lost River, which contains up to 28 percent topaz, contains almost 8 percent fluorine, equivalent to about 16 percent CaF_2 .

In the Kigluaik Mountains, about 40 miles (65 km) north of Nome, fluorite cements breccia in two pipes along a tributary of the Tisuk River. The pipes consist of angular jasperoid fragments cemented by fluorite. The largest measures at least 80 feet (25 m) long and 20 feet (6 m) wide. Tourmalinized granite crops out nearby and elsewhere in the vicinity, suggesting that other pipes may exist.

Fluorite has long been known at scattered localities in a limestone area about 20 miles (32 km) north of Nome (Eakin, 1915; Herreid, 1966). Trenching has disclosed that fluorite accompanies barite in a brecciated and dolomitized marble intercalated in chloritic schist of the Precambrian Nome Group. Anomalous amounts of lead, zinc, silver, and gold accompany the fluorite and barite. Because other marble beds probably occur beneath the one exposed by trenching, fluorite may be found at greater depths and may be of economic value (Brobst and others, 1971). Moreover, fluorite may be found beneath some of the many gossans known elsewhere in this general region (Eakin, 1915).

In the eastern part of the Seward Peninsula, an extensive belt of granitic rocks is accompanied by a varied suite of alkalic rocks (Miller, 1971). Fluorite has been noted at many localities in this general region (Vivian Velette, oral commun., 1968), for instance, in a fine-grained intrusive at the southeast end of the Bendeleben Mountains. According to Thomas P. Miller (oral commun., 1970), fluorite in small amounts is widespread where alkalic rocks intrude limestones. According to A. A. Beus (oral commun., 1967), large fluorite deposits associated with alkalic rocks are known in nearby Siberia. Hence, the geologically similar east part of the Seward Peninsula is shown as a possible fluorine-rich province which may contain undiscovered fluorite deposits.

Fluorite in minor amounts is known at many places in Alaska outside the Seward Peninsula. The most significant are shown on the map by Worl, Van Alstine, and Heyl (1974); in 1973 none were economically important.

At Bokan Mountain, southeastern Alaska, a peralkalic granite and the adjoining rocks contain small amounts of

fluorite associated with uranium ores, but the individual deposits and the total amount of fluorite are small (E. M. MacKevett, Jr., oral commun., 1971).

In Glacier and Groundhog Basins, southeastern Alaska, where substantial deposits of lead and zinc are known, sulfide-bearing veins have a gangue of quartz and fluorite, and a large breccia vein as much as 40 feet (12 m) thick contains notable fluorite, as do other quartz veins nearby (Gault and others, 1953, p. 23). Large breccia pipes as much as 400 feet (120 m) in diameter are known in the area. They contain some fluorite and topaz, but have not been evaluated for fluorite at depth.

Fluorite in float or bedrock occurs sporadically across central and eastern Alaska from the Eagle area to west-central Alaska, along a belt which contains placer tin associated with granitic rocks of Late Cretaceous to Tertiary age. No deposits of economic promise are known. If lode tin deposits are found fluorite and (or) topaz in larger amounts are likely to be associated.

In the eastern Brooks Range, near Mount Michelson in northern Alaska, fluorite occurs near and in a granitic batholith. Veins and veinlets are associated with altered rocks containing greisen or tourmaline.

On Zarembo Island in southeastern Alaska, volcanic rocks of Tertiary age contain narrow veins and breccia zones which have chalcedony covered by fluorite. One breccia zone ranges from a few inches to several feet in thickness, with breccia fragments coated with chalcedony on which fluorite was deposited as incrustations (Buddington, 1923). This is the only fluorite lode in Tertiary volcanics reported in Alaska.

Fluorine resources in Alaska in minerals other than fluorite consist principally of fluorine in topaz greisen, and in phosphate rock. The known deposits of size are at Lost River, on the Seward Peninsula, where topaz greisen forms a mass in the buried granite that measures several hundred feet across and extends vertically several hundred feet deep. However, much of this greisen was argillized, and argillization destroyed the topaz without fixing all the fluorine in late-stage fluorite; the general fluorine content probably averages not more than 3-4 percent.

The granite at Tin Creek, about 2 miles southeast of the Lost River mine, also is greisenized over an area of several thousand square feet on the northeast end; the topaz content is unknown, though considerable.

The phosphatic limestones of northern Alaska were discussed by Patton and Matzko (1959), who concluded that high-grade phosphate rock (35.8 percent P_2O_5) occurs in the Shublik Formation of Triassic age, and lower grade phosphate rock is present in the Lisburne Group of late Paleozoic age. Fluorine is present in the phosphate rock in carbonate fluorapatite and also in fluorite. As both these units crop out for a hundred miles along the Arctic foothills of the Brooks Range, they unquestionably contain large resources of fluorine as well as of phosphate.

WASHINGTON-IDAHO-MONTANA-WYOMING-SOUTH DAKOTA

By R. L. PARKER

Fluorite is widely distributed in the Washington, Idaho, Montana, Wyoming, and South Dakota region; only a few deposits, however, are known to be of sufficient size and grade to be of commercial interest, and known resources are not large. The only deposits in the region with significant recorded production are the Challis and Meyers Cove deposits, Idaho, and the Snowbird, and Crystal Mountain deposits, Montana. Of these deposits only the Crystal Mountain has been a consistent producer.

Fluorite deposits in the region can be grouped into several types. The most important deposits are associated either with volcanic rocks or with intrusive rocks of the Colville, Idaho, and Boulder batholiths and alkalic intrusive bodies. In addition to different volcanic and intrusive associations, the fluorite deposits in the region have different structural characteristics. Fillings of fissures and breccias by fluorite and chalcedony with vuggy, drusy, and layered features common to epithermal deposits are characteristic of fluorite deposits related to large volcanic piles in Washington and Idaho. One of the most prevalent types of occurrence is related to the contact between intrusive and sedimentary rocks, especially between granitic and alkalic intrusive rocks and limestone or other calcareous rocks. Fluorite at such deposits is concentrated in veins or breccia zones in both intrusive and country rocks, is disseminated in the intrusive rocks, or is disseminated or concentrated in sedimentary rocks along the contact. Some deposits are actually in the contact metamorphic aureole of the intrusives and are associated with tactite or skarn. Other deposits are in pegmatites that are in genetically related intrusive rocks or in country rocks. Certain occurrences of fluorite are obscure in their origin, and although they are found as gangue in vein deposits of metallic minerals, they may be unrelated except for the site of localization. Miscellaneous occurrences include fluorite as gangue in uranium deposits, and at least one fluorite deposit that is considered to be of evaporite origin.

Deposits and occurrences of fluorite are described according to State in the order: Washington, Idaho, Montana, Wyoming, and South Dakota.

DESCRIPTIONS OF INDIVIDUAL DISTRICTS AND DEPOSITS. WASHINGTON

Fluorite occurs in a gold-silver-selenium deposit in the Republic district, Ferry County. The fluorite is locally present in chalcedony-calcite veins that are contained in Tertiary volcanics (Bancroft, 1914; Van Alstine, 1966).

Fluorite is contained in quartz-calcite-chalcopyrite veins in the Zalla M, American Flag, and Silver Bell deposits in the Sheridan area, Ferry County. Some zones contain as much as 30 percent fluorite, but their extent is not known. The deposits are in Tertiary volcanics (Valentine, 1949; Van Alstine, 1966).

Fluorite is reported at one place in the upper part of the Ethel vein, in Snohomish County. The fluorite occurs with quartz, calcite, and bornite in granodiorite (Weaver, 1912; Van Alstine, 1966).

Fluorite is contained in veins 2-12 inches (5-30 cm) thick in the Three Pinnacles-Lost River deposits, in Okanogan County. The fluorite is associated with chalcedony in the veins which cut granite (Valentine, 1949; Van Alstine, 1966).

Seven parallel veins of fluorite and chalcedony occur at the Slide deposit, in Chelan County. The veins range in thickness from less than 1 to 6 inches (2.5-15 cm) and are traceable for only a few feet in a zone 300 feet (90 m) across in granite (Valentine, 1949; Van Alstine, 1966).

Fluorite is a gangue mineral in a silver ore vein that cuts granite of the Colville batholith at the Apache claim, in Okanogan County. The vein is a quartz vein irregularly banded with pyrite, fluorite, and an unidentified black sulfide mineral (Valentine, 1949; Pardee, 1918; Van Alstine, 1966).

Fluorite is found in veins and shear zones in Ramore, Gladora, and Wasco lead-silver-zinc-copper deposits in the Park City district, in Okanogan County. The fluorite, in minor amounts, is associated with quartz, metallic sulfide minerals, calcite, and sericite in deposits in quartz monzonite of the Colville batholith (Pardee, 1918; Van Alstine, 1966).

The Mitchem fluorspar deposit is in Ferry County. It is the only productive deposit in Washington, having produced a small tonnage of acid grade and metallurgical fluorspar as follows: 60 tons in 1918, 152 tons in 1940-42, and 170 tons in 1945-46. The fluorspar is contained in a 16-inch (40-cm) steeply dipping northwest-trending vein in granitic rock of the Colville batholith. The vein contains green, purple, and colorless fluorite, calcite, chalcedony, and some pyrite. Across mining widths, the material averages about 50 percent CaF_2 . The deposit is considered to be small (Van Alstine, 1966) and not to constitute a large reserve on the basis of available data.

Thin veinlets of fluorite occur in limy argillite at the Montgomery deposits, in Okanogan County (Valentine, 1949).

Fluorite is a minor gangue mineral associated with quartz, ferberite, scheelite, pyrite, molybdenite, and chlorite in tungsten veins at the Germania mine, in Stevens County. The veins are mostly less than 3 feet (1 m) thick and are contained in Cretaceous quartz monzonite (Becraft and Weis, 1963; Van Alstine, 1966).

Fluorite occurs as a gangue mineral with wollastonite, tremolite, and quartz in the magnetite ore body at the Read iron deposit, in Stevens County. Mineralized rock is localized along a granite-limestone contact and fluorite is in a contact-metamorphic zone. Associated ore minerals are scheelite, chalcopyrite, and magnetite (Valentine, 1949; Van Alstine, 1966).

Fluorite occurs in molybdenite-bearing quartz veins and as an accessory mineral in adjacent granite especially near schist and quartzite contacts at the Phalen Lake molybdenum deposit, in Stevens County (Valentine, 1949; Van Alstine, 1966).

Fluorite is a minor constituent in the quartz veins of the Northport district, Stevens County. The quartz veins bear sulfide minerals and are contained in argillite and limestone cut by granite and in black slate of Paleozoic age (Van Alstine, 1966).

Fluorite is reported in small lenses in gneiss and schist about 5 miles (8 km) east of Riverside, in Okanogan County (Valentine, 1949; Van Alstine, 1966).

Fluorite at the Electric City deposit occurs in pegmatite lenses in granite of the Colville batholith, in Douglas County. Associated minerals are quartz, molybdenite, and pyrite (Van Alstine, 1966).

Fluorite is contained in pegmatite in granite of the Colville batholith at the Sanpoil uranium deposit, in Okanogan County. The fluorite is violet, radioactive, and associated with samarskite (Van Alstine, 1966).

Fluorite occurs as traces in gray massive quartz segregations in muscovite-rich pegmatites that cut fine-grained monzonite of the Loon Lake Granite at the Spokane molybdenum deposit, in Lincoln County (Becraft and Weis, 1963).

IDAHO

MEYERS COVE

The Meyers Cove fluorspar district, Idaho (Anderson, 1954a; Cox, 1954), is about 38 miles (61 km) (66 miles by road) southwest of Salmon, and 26 miles (42 km) northwest of Challis, Lemhi County, on Camas Creek, a tributary of the Middle Fork of the Salmon River. The deposits produced about 37,432 tons of fluorspar during 1951-53, principally from the Big Lead deposit. Other deposits in the district are North Pit, Anderson, Bear Trap, M and M, and Chamac.

The fluorspar deposits are fissure fillings along northeast-trending zones which Anderson (1954a) attributed to a deep-seated shear in basement rocks. The deposits are located in Challis Volcanics (Tertiary) and Miocene porphyries, but these host rocks apparently had little effect on localization of the deposits. The deposits are exposed over a vertical range of more than 2,000 feet (610 m).

The ore bodies vary widely in size, ranging from a few inches in width and a few tens of feet in length to more than a dozen feet in width and several hundreds of feet in length. They average 4-5 feet (1.2-1.5 m) in thickness with thicker local bulges and are 100-300 feet (30-90 m) long. Big Lead has a maximum stope width of 16 feet (5 m) and stope length of 300 feet (90 m). Ore bodies tend to swell where the orientation of fissures changes from northeast to

The mineral assemblage of the deposits is simple, consisting chiefly of chalcedony, fluorite, and some barite. The ore is layered (commonly called "banded"), and chalcedony and cryptocrystalline fluorite form concentric shells on breccia fragments and form crystalline druses.

The wallrocks along fluorite-bearing zones are commonly bleached and (or) stained with iron oxides. The bleaching resulted from argillic alteration, with limited sericitic alteration close to fluorite bodies. Some of the iron staining is attributed to the oxidation and decomposition of pyrite. In places, silicified rocks are closely associated with the fluorite bodies.

The Meyers Cove deposits are probably epithermal as indicated by the low-temperature layered chalcedony and the open-brecciated, vuggy and drusy nature of the ore which suggests near-surface deposition. The fluorite bodies were deposited in fissures along northeast-trending zones probably from hydrothermal solutions.

These deposits have high potential as a future resource of fluorspar.

BAYHORSE

The Challis fluorspar deposits (Bayhorse district), Custer County (Anderson, 1954b), are located in the northern part of the district about 4 miles (6.5 km) southwest of Challis at the south end of the Salmon River Mountains.

Fluorite was not recognized as a gangue mineral in the silver base-metal lodes of the Bayhorse district until the early 1940's. Actual location of claims for fluorspar dates from 1947, and exploration, development, and small production was not until 1952-53 in the Keystone Mountain-Daugherty Gulch area. Production from the Chalspar No. 1 deposit amounted to 475 tons of metallurgical-grade fluorspar and 245 tons of lower grade material.

The Challis fluorspar deposits are fissure fillings and breccia impregnations in which abundant open spaces and fluorite-lined druses are characteristic. All deposits reported are in the Bayhorse Dolomite of Ordovician(?) age, which forms a favorable host because it is more brecciated than adjacent formations (Anderson, 1954b, p. 7). The major structural feature of the area is the Bayhorse anticline that exposes lower Paleozoic rocks comprising several formations: Garden Creek Phyllite, Bayhorse Dolomite, Ramshorn Slate, and Kinnikinic Quartzite. Fissure veins and breccia lodes are localized along faults and relatively minor fault zones wholly within the Bayhorse Dolomite. Most veins have northerly trends and steep westerly dips. Fluorspar bodies reach widths of several tens of feet and lengths of several hundred feet. The Passed Up vein, for example, is 3-7 feet (1-2 m) thick and is exposed for more than 200 feet (60 m) along strike. The vein on Chalspar No. 2 claim is 12-18 feet (3.7-5.5 m) thick and is exposed for 900 feet (275 m). Some breccia deposits range in diameter from a few feet to 30 feet (9 m) and can be traced for a hundred feet or more at the surface.

The deposits consist chiefly of fluorite with minor amounts of quartz and calcite. In some veins local masses of sulfides are relict from earlier mineralization. Some breccias have boxwork structure in which quartz forms thin partitions between cells and is coated with fluorite. Layering ("banding") is not conspicuous, but poorly defined concentric layers of fluorite enclose breccia fragments.

The grade of the fluorspar is variable and most deposits require milling to upgrade the material sufficiently for commercial use. Samples across the Passed Up vein averaged 67.1 percent and 57.1 percent CaF_2 over widths of 13 and 14 feet (4 and 4.3 m), respectively. At the Chalspar No. 5 the vein ran 40 percent CaF_2 over a width of 17 feet (5.2m). The boxwork breccias at Keystone Mountain assayed 30-60 percent CaF_2 across 18-30 feet (5.5-9 m).

The age of fluorspar mineralization is considered to be Oligocene or younger, because probable Oligocene volcanic rocks form the hanging wall of the Passed Up vein.

The district has large potential as a future source of fluorspar. Surface exposures and limited exploration indicate fluorspar bodies sufficiently large for mining. Although the grade is lower than some currently mined deposits, future prices may be sufficiently high to allow beneficiation and shipment to centers of consumption.

STANLEY AREA

Fluorite has been discovered in the Stanley area, Custer County (Choate, 1962), in the following localities: (1) in epithermal gold-silver veins in quartz monzonite-granodiorite near the mouths of Big and Little Casino Creeks about 3.5 miles (5.5 km) east of lower Stanley; (2) in fluorite veins in the Challis Volcanics at the Lamb prospect in the northern part of the Yankee Fork district 1 mile (1.6 km) west of Jordan Creek-Mayfield Creek divide; and (3) in a gold-silver vein in Challis Volcanics on Hindman Peak Ridge 1.25 miles (2 km) south of Red Mountain about 13 miles (20 km) north of lower Stanley (no description is available). The known deposits containing fluorite are the Bright Star, the Giant Spar, the Homestake, and the Gold Chance properties, and the Hide Out and the Lamb prospects. The only production of fluorspar recorded from any of these deposits was from the Giant Spar which reportedly yielded a few truckloads of fluorite during World War II.

The Giant Spar is the largest known fluorite deposit in the Stanley area. It occurs as epithermal, open-space filling in faults and breccia zones in quartz monzonite-granodiorite. Other fluorite-quartz veins of the district have been explored for gold and silver, but these metals are not present in the fluorite of the Giant Spar. Diamond drilling has indicated a composite vein system that trends northeast and has a maximum thickness of about 15 feet (4.5 m). The fluorite vein is cut by a younger fault. A chip sample across a 10.6-foot (3.2-m) width of the vein contained 71.5 percent CaF_2 . Rhyolite and basalt dikes cut the

quartz monzonite in the vicinity of the deposit, but the relation of the fluorite to the dikes was not stated by Choate (1962). Presumably the fluorite mineralization was related to Challis volcanism.

The fluorite is pale lavender, colorless, and pale green, and forms "banded" veins. Vugs are common and some are lined with euhedral fluorite crystals.

The Bright Star deposit contains a composite fluorite vein zone 3 feet (1 m) thick composed of individual veins of fluorite up to 6 inches (15 cm) thick and stringers of quartz. The vein zone contains 60–80 percent fluorite. The extent of the deposits is unknown because of the caved condition of the workings.

The Homestake, Gold Chance, and Hide Out claims contain minor fluorite in gold-pyrite-quartz-fluorite veins. The Hide Out workings are anomalously radioactive.

The Lamb prospect in the northern part of the Yankee Fork district contains fluorite in a series of veins, stringers, and breccia fillings along a northeast-trending zone that is at least a mile (1.6 km) long and several hundred yards wide. The zone cuts the Challis Volcanics. The largest vein in the zone is traceable for 600 feet (180 m) and ranges in thickness from a few inches to 4 feet (1.2 m). A sample across a 4-foot (1.2-m) vein width contained 39.4 percent CaF_2 and showed fluorite, calcite, chalcedony, quartz, and breccia; no metallic minerals were detected.

Too little information exists on the Stanley fluorite deposits to assess their potential. Some veins are high enough in grade and are wide enough to merit investigation of their vertical and longitudinal extent in order to determine the presence or absence of minable ore bodies.

BIG SQUAW CREEK

The Big Squaw Creek fluorspar deposit, previously known as the Smothers property or the Noussan mine, is located on the Salmon River between Big Squaw Creek and Smith Gulch in the Salmon River Breaks Primitive Area. It is 18 miles (29 km) downriver from the end of the road at Corn Creek. The description of the deposit presented here is based on Weis and others (1972).

The deposit was prospected for gold as early as 1860, but was not claimed until 1937. Properties have passed through considerable reassignment and relocation to the present time. Exploration under a contract with Defense Minerals Exploration Administration was conducted in 1957–58 including geologic mapping, trenching, and diamond drilling as well as additional work by the owners. No production has been recorded from the claims although inferred reserves are considered to be about 100,000 tons of fluorspar containing 70 percent CaF_2 .

The fluorspar deposit consists of three ore shoots on the hanging wall (or east side) of a persistent quartz vein that strikes N. 10° W. and dips 60° E. The vein is contained in biotite gneiss that is intruded by quartz monzonite about a mile (1.6 km) to the west. The vein is one of many quartz

veins that occur in a zone trending N. 10°–15° W., and so far as known, contains the largest bodies of fluorite.

The fluorite is present as small stringers and as crystals lining vugs in the quartz vein, and as ore shoots along the hanging wall of the vein. It is both massive and coarsely granular and ranges from transparent through green to purple.

Three ore shoots have lengths of 600, 260, and 220 feet (180, 80, and 67 m) and average widths of 7.2, 7.9, and 7.1 feet (2.2, 2.4, and 2.2 m), respectively. Average grades of the shoots as determined from surface samples are 67.50, 73.93, and 70.50 percent CaF_2 respectively. Diamond drilling on the 600-foot-long shoot mentioned above indicates that it extends to a depth of at least 300 feet (90 m) but may decrease in grade in depth.

The deposit is apparently related to the Idaho batholith because of its proximity thereto, and has certain features in common with the Crystal Mountain, Spar, and Snowbird deposits of Montana. Although 100,000 tons of ore with a grade of 70 percent CaF_2 is inferred for the deposit, it remains submarginal because of its remoteness.

OTHER DEPOSITS

A narrow vein of high-grade fluorite is reported to occur in the Pungo Creek area, Valley County (Anderson and Van Alstine, 1964). The vein is in porphyritic diorite cut by mafic dikes.

Fluorite occurs in a northeast-trending vein at the Simer prospect, 6 miles (9.7 km) north-northwest of Salmon. The vein is composed mostly of radioactive jasperlike rock as much as 2–3 feet (1 m) thick. It cuts quartz monzonite and contains monazite, variable amounts of barite, and purple and colorless fluorite (Anderson, 1959, p. 89).

Fluorite occurs in a number of gold lodes in the Edwardsburg district, Valley County, but is most abundant in upper Smith Creek at the Independence mine. The fluorite is disseminated in coarse grains in irregular quartz veins 3 feet (1 m) or more in width which occur at intervals in a silicified zone that is several thousand feet long and 200 feet (60 m) wide (Clyde P. Ross, in Burchard, 1933, p. 14). The deposit is in the Precambrian Y Yellowjacket Formation that in the vicinity of the mine consists mainly of schistose argillites and quartzites and a layer of crystalline limestone at least a hundred feet (30 m) thick. The silicified rock contains scattered sulfides: pyrite, sphalerite, tetrahedrite, and galena (Shenon and Ross, 1936, p. 28).

Fluorite is a gangue mineral in tungsten-bearing quartz veins in quartzite in the Blue Wing district, Lemhi County. According to Callaghan and Lemmon (1941) it is prominent only in a zone extending 600 feet (180 m) from the granite contact on the intermediate level of the Ima mine where it bears a definite zonal relation to the granite. Associated minerals in the veins are orthoclase, rhodochrosite, huebnerite, pyrite, tetrahedrite, chalcopyrite, bornite, galena, sphalerite, molybdenite, and scheelite. Some fluorite is also disseminated in the granite.

Fluorite occurs as a minor accessory mineral associated with aquamarine disseminated in albitized quartz monzonite in certain parts of the Sawtooth batholith in central Idaho (Reid, 1963).

MONTANA

CRYSTAL MOUNTAIN

The Crystal Mountain fluorite deposit is located on the Rye Creek-Sleeping Child Creek divide, in the southwestern part of Ravalli County. It is 26 miles (42 km) by road east of Darby and lies at an elevation of about 6,800 feet (2,100 m).

The deposit consists of two separate groups of outcrops about 3,000 feet (900 m) apart. An eastern group, called the Retirement claims, consists of two small elliptical outcrops of fluorite 60 feet (18 m) wide and 150 feet (45 m) long. The fluorite bodies are more resistant to erosion than the enclosing rocks and hence form the crests of knolls (Taber, 1953). Sahinen (1962) suggested that the bodies are erosion remnants of a flat-lying vein and described the enclosing rock as granite and fine-grained gray gneiss with an overlying mass of white quartz in the hanging wall and veinlets of glassy quartz in the footwall.

A larger western group, called the Lumberjack claims, is the site of an open pit mine. This group consists of three main bodies of fluorite 100–200 feet (30–60 m) wide and 200–400 feet (60–120 m) long which are tabular and dip easterly 10°–35°. These bodies, according to Weis and others (1958), are underlain by coarse-grained biotite granite that contains inclusions of hornblende-plagioclase gneiss, biotite-quartz-plagioclase gneiss and pegmatitic granite. Foliation in the inclusions strikes about north and dips 20°–30° E. nearly parallel to the fluorite bodies. Small dikes of granite cut both gneiss and fluorite.

The fluorite at the Crystal Mountain deposit is exceptionally high grade and remarkably uniform in quality. The average grade (Sahinen, 1962) is more than 96 percent CaF_2 . Weighted averages of nine samples taken by the U.S. Bureau of Mines (Taber, 1952) contained 97.2 percent CaF_2 , 1.44 percent SiO_2 , and 0.13 percent Fe. The ore consists of massive crystalline fluorite and local minor amounts of biotite, quartz, feldspar, sphene, rare-earth-bearing apatite, amphibole, fergusonite, thorianite(?), and thortveitite (Parker and Havens, 1963). The fluorite ranges in crystal size from 0.1 inch to at least 1 inch (2.5 mm–2.5 cm) across and ranges in color from white through pale green to deep purple. The minor minerals are concentrated in deep-purple fluorite aggregates that are radioactive and which occur mostly at the margins of the fluorite bodies. Spectrographic analysis of run-of-the-mine fluorite shows the presence of minor aluminum, magnesium, barium, nickel, titanium, and niobium; analysis of the dark-purple fluorite indicates amounts of iron, potassium, aluminum, silicon, uranium, thorium, niobium, rare earths, yttrium, phosphorus, and scandium higher than the average mined fluorite.

The Crystal Mountain deposit is distinguished by several characteristic features. The ore bodies are nearly pure fluorite and are sharply delineated from the enclosing host granite that is considered to be part of the Idaho batholith. Younger granite(?) dikes cut both fluorite and enclosing host granite. The host granite also contains ordinary quartz-feldspar pegmatites. Radioactive fluorite which contains an anomalous content of rare-earth elements, niobium, thorium, and scandium forms zones roughly bordering the fluorite bodies. Some minerals enclosed in radioactive fluorite are found commonly in pegmatites. Indeed, thortveitite has been found only in pegmatites.

The origin of the Crystal Mountain deposit is not clear. The characteristics mentioned above point to a plutonic origin related to pegmatites. The deposits of fluorite might be considered to be monomineralic pegmatites.

SNOWBIRD

The Snowbird deposit, also known as the F and S fluorite mine, is located on the Montana-Idaho Boundary at the head of Cedar Log Creek, just below the crestline of the Bitterroot Range in southwest Mineral County. The deposit, which is covered by 19 unpatented claims, was mined for fluorite in 1956–57 by the F and S Mining Co., producing approximately 6,500 short tons of metallurgical-grade fluorite. The ore reportedly has been exhausted (Sahinen, 1962).

The Snowbird has certain features that suggest genetic similarities with the Crystal Mountain and Spar deposits. The deposit is a zoned quartz-calcite-fluorite body that Clabaugh and Sewell (1964) described as a carbonatite "pegmatite." It is discordantly intruded into the Precambrian Wallace Formation of the Belt Supergroup which at this locality consists of argillite, argillaceous limestone, slate, and limy quartzite. These rocks are intruded by rocks of the Idaho batholith south of the deposit, and in the vicinity of the deposit they have been sufficiently thermally metamorphosed to produce metacrysts of scapolite in the argillaceous beds (Sahinen, 1962).

The fluorite deposit lies in a pegmatite pod that is at least 600 feet (180 m) long and 100 feet (30 m) wide and has an east-west long axis. The major part of the pod is massive white quartz that forms the hanging wall of the main fluorite body. The quartz mass contains no inclusions, but euhedral crystals of quartz can be recognized protruding from the mass and some crystals are as much as 20 feet (6 m) long (Clabaugh and Sewell, 1964). The quartz forms an incomplete envelope around the calcite body, and fluorite is located in pockets in the calcite at the calcite-quartz contact. Two main bodies of fluorite were 120 feet (37 m) and 40 feet (12 m) long. The fluorite assayed 96.2–96.5 percent CaF_2 (Sahinen, 1962).

The deposit contains—in addition to quartz, calcite, and fluorite—gersdorffite (NiAsS) and parisite [$\text{Ca}(\text{Ce},\text{La},\text{Y})_2(\text{CO}_3)_3\text{F}_2$]. These rare minerals have not

been noted in other fluorspar deposits in the region, but rare-earth elements, especially yttrium, are associated with fluorite at the Crystal Mountain deposit near Darby. The Snowbird deposit is of pegmatitic origin and is probably related to the Idaho batholith.

SPAR

The Spar mine is located on the ridge between Dry Creek and Bear Creek, in central Mineral County about 12 miles (19 km) west of Superior (Ross, 1950; Sahinen, 1962).

The Spar claim was originally located in 1943 by Mr. Joseph Brooks and was developed in 1944, during which time an unknown amount of ore was mined. Additional fluorspar deposits were discovered nearby in 1948 in the Wilson Creek drainage south of Dry Creek and in 1949 in nearby Lime Gulch. The Spar and Wilson Creek properties, under control of various subsequent operators, together produced 318 tons of fluorspar in 1948, 422 tons in 1949, and 41 tons in 1950 (last reported production). Individual property production is not known.

The Spar deposit is localized in the Wallace Formation of the Precambrian Belt Supergroup which in the area consists of quartzite, argillite, calcareous quartzite, dolomite, and ferruginous limestone; most of the rocks strike northwest. The rocks in the vicinity of the deposit have undergone moderately intense and somewhat irregular folding, and locally contain steep, sheeted zones and zones of intense brecciation. Conspicuous lenticular milky-white quartz bodies cut the Wallace Formation, and at least one of them contains fluorite (Spar mine). In the general area of Ann Arbor and Bear Creeks quartz lenses exceed 100 feet (30 m) in length, and some crop out along a nearly straight line. The lenses are discordant and show no parallelism or obvious relation to the trends of the beds of the Wallace Formation that they cut. The larger lenses of quartz trend N. 70° E. to S. 70° E. and have northwest-trending joints.

Igneous rocks are not exposed in the area. The Idaho batholith which lies about 35 miles (55 km) to the south and a diabase sill about 10 miles (16 km) to the west are the closest known occurrences of igneous rocks.

The fluorspar at the Spar mine occurs in irregular pods and lenses ranging in diameter from several inches to several feet. A sample cut by Clyde P. Ross (1950, p. 208) across a 45-inch (1.5-m) face in the main pit at the Spar property assayed 98.57 percent CaF_2 , 1.18 percent SiO_2 , and 0.14 percent carbonate.

The fluorite at the Spar property occurs with calcite and ankerite and minor galena, tetrahedrite, and pyrite. A large body of milky-white quartz 30 feet (9 m) wide and 150 feet (45 m) long forms the hanging wall. Some large crystals of quartz a foot or more across are exposed in the Spar prospect.

The Spar fluorspar deposit resembles the Snowbird deposit in some respects. Both deposits lie in the calcareous Wallace Formation of the Belt Supergroup and

both are associated with calcite and minor sulfides and with massive milky-white quartz bodies containing large quartz crystals suggestive of pegmatitic origin. Neither deposit can be related directly to visible igneous rocks although the Snowbird deposit is close to exposed rocks reported as part of the Idaho batholith.

OTHER DEPOSITS

The Jetty mine, also known as the Balkan lode, is on the north slope of Garrity Hill, 6 miles (10 km) west of Anaconda, Deer Lodge County. Fluorite occurs as a gangue mineral in a metalliferous vein at an intermediate level in the mine. The vein is composed of quartz, fluorite, barite, and the metallic sulfides—boulangerite, pyrite, sphalerite, tetrahedrite, and stibnite. Host rock of the deposit is Madison Limestone (Mississippian) and Quadrant Quartzite (Pennsylvanian). Intrusive rocks of Boulder batholith age occur in the region. The extent of fluorite in the mine is not known but the mineral might be recovered as a byproduct in the milling of the sulfide ore (Sahinen, 1962).

The Weathervane Hill prospect lies south of the Smelter stack at Anaconda, in Deer Lodge County. Fluorite occurs in a fault zone between upper Paleozoic limestone and upper Mesozoic strata. The fluorite is distributed irregularly in pockets a few inches to a few feet in maximum dimension. The potential for commercial fluorspar is low for anything but very small-scale mining (Sahinen, 1962).

The Silver Bow deposits are 6 miles (10 km) west of Butte along Silver Bow Creek, in Silver Bow County. Interstate Highway 90 (U.S. Highway 10) and four railroads cross the property. The Bull Moose, Merrimac, and Wrong Font are claims in this group of deposits. Fluorite occurs in shoots within a gold-silver(?) bearing fracture zone along a fault(?) contact between andesite and quartz monzonite and aplite. The mineralized zone extends more than 2,000 feet (600 m) in a northwest direction and in places is more than 100 feet (30 m) wide. The rocks in the zone are silicified and stained with iron oxides. The principal bodies of fluorspar are on the east end of the Bull Moose claim where layers of fluorite range from an inch (2.5 cm) to 3.5 feet (1 m) in width and are tens of feet in length. An average of six samples gave 83.84 percent CaF_2 , 13.02 percent SiO_2 , 2.02 percent R_2O_3 , and 1.40 percent CaCO_3 (Sahinen, 1962; Ross, 1950). Exploration has been insufficient to define the extent of fluorspar at the deposits; the grade and size of bodies reported, however, would indicate potential for small-scale mining. Actual operations might be hampered by the highway right-of-way that runs through the properties.

The Bald Butte mine lies within the Marysville mining district, 17 miles (22 km) northeast of Helena, Lewis and Clark County, and 3.5 miles (5.5 km) southwest of the old mining camp of Marysville. Fluorite occurs with quartz as the gangue of metallic ore that was originally developed and mined by underground workings that are no longer

accessible. The deposit is in limestone of the Helena Formation of the Precambrian Belt Supergroup which has been intruded and hornfelsed by dikes and sheets of microdiorite and later cut by diorite porphyry dikes of Belmont Porphyry. All these rocks are shattered, and infiltrated with quartz and fluorite. The deposit may be related to a porphyry of middle Tertiary age. Sahinen (1962) concluded from the examination of dump specimens and Barrell's (1907) description of the deposit that no fluorite ore could be marketed from the deposit without extensive beneficiation.

The Boeing prospect is located about 3.5 miles (5.5 km) west of Austin in the Austin mining district, Lewis and Clark County. Fluorspar is contained in small irregular pods in the Madison Limestone adjacent to an altered and mineralized biotite rhyolite dike. The limestone is intruded by quartz monzonite a short distance south of the deposit. The principal fluorite body was 3–6 feet (1–2 m) wide and exposed over a height of 7 feet (2.1 m). A sample taken near the surface across a 41-inch (1.1-m) width yielded 81.76 percent CaF_2 , 10.09 percent SiO_2 and 2.52 percent carbonates (Ross, 1950). The extent of the fluorspar has not been determined, but reports indicate that fluorite bodies are small and irregularly distributed.

In the Sweetgrass Hills in northwestern Liberty County, just south of the Canada-United States boundary the principal fluorspar bodies are in Tootsie Creek (Ross, 1950; Sahinen, 1962); they consist of veins, replacement seams, and minor disseminations in or adjacent to marbleized Madison Limestone near contacts with porphyritic syenite of the laccoliths and stocks of the Sweetgrass Hills. Most of the fluorspar masses closely follow bedding or sheeting in the limestone. Some masses are irregular, some nearly flat, and others roughly spherical. Some mineralized zones attain widths of 10 feet (3 m) and some can be followed continuously along strike for as much as 50 feet (15 m). Most individual bodies are much smaller and are scattered in the Tootsie Creek area through a zone in limestone that is well over 2,000 feet (600 m) long and at most is several hundred feet wide. The fluorite is intimately intergrown with other minerals; a 200-mesh grind is required to release the fluorite and obtain a 95-percent CaF_2 concentrate. The CaF_2 content of the mineralized material ranges from 3.06 to 87.01 percent averaging somewhat less than 40 percent in bodies of minable size. The silica content ranges from 1.68 to 43.83 percent. The area has potential for minable fluorspar bodies, but exploration has been insufficient to define the extent of fluorite mineralization.

Minor fluorite is reported in the South Moccasin Mountains, a satellite uplift of the Judith Mountains intrusive center (Miller, 1959; Sahinen, 1962). The fluorite occurs as a gangue mineral in a gold-silver vein, in a dickite clay body, and in an area of breccia and altered rock adjacent to a large fault. All the deposits are related to

alkalic rocks—porphyritic syenite and leucorhyolite—which intrude the Madison Limestone. Fluorite is also reported in at least one zone within the intrusive rock.

At the American Flag prospect near the summit of Judith Peak, Fergus County, fluorite and quartz form a 10-foot (3-m) vein that cuts an altered zone in a syenite intrusive in the Judith Mountains alkalic intrusive center (Sahinen, 1962). The vein also contains lead, silver, and gold. Another nearby occurrence of fluorite is in fine seams and disseminated grains in a 5-foot (1.5-m) tinguaitite dike. The fluorite-quartz vein contains 22.8–34.0 percent CaF_2 , 52.8–66.9 percent SiO_2 , 2–4 percent lead, 0.1–0.5 ounce silver per ton, and a trace of gold. Other, perhaps major, fluorspar deposits are veins and replacement seams in Madison Limestone in and near the mine. The property was being developed in 1971 (R. G. Worl, oral commun., 1971).

Fluorite at Antone Peak in the Little Rocky Mountains, in Phillips County (Sahinen, 1962), is sparsely disseminated in porphyritic syenite that intrudes sedimentary rocks of varied lithology ranging in age from Middle Cambrian to Late Cretaceous.

An occurrence of fluorite is reported in the Pryor Mountains at the Old Glory mine, 12 miles (19 km) east of Warren, Carbon County (Sahinen, 1962). Fluorite is associated with uranium minerals in the Madison Limestone. The fluorite occurs as ovules and spheroids that have concentric structure and are considered to be replacements of oolitic structures in the limestone.

WYOMING

Several deposits of fluorite in the Bear Lodge Mountains about 10 miles (16 km) north of Sundance occur in a north-trending zone about 0.5 mile (0.8 km) wide and about 3 miles (5 km) long. Production of fluorspar from the district has been less than a ton. Fluorite is localized in limestone and sandstone that are intruded by Tertiary hypabyssal alkalic rocks (phonolites and trachyte porphyries). Bodies of fluorite for the most part are only a few feet long and are in the form of lenses parallel to bedding planes. Some fluorite is disseminated in the Minnelusa Sandstone and some is found in veins in a breccia zone in the intrusive rocks. The fluorite is associated with calcite, quartz, siderite, and orthoclase. CaF_2 content of the fluorite lenses ranges from 5 to 90 percent (Osterwald and others, 1959, p. 69). The deposits are similar in some respects to the central Montana occurrences in which alkalic and carbonate rocks are the hosts of the deposits.

Fluorite is reported in a pegmatite in granite at the Bear deposit, in Laramie County. Twenty tons of fluorite was stockpiled in 1944 as a byproduct of feldspar mining (Osterwald and others, 1959).

In the northern part of the Bighorn Basin a carbonate rock sequence of Permian age is reported by De Koster (1960, p. 53–55) to contain 12–15 percent fluorite. This fluorite is considered to be of primary sedimentary origin

as a precipitate from saline waters at a stage in evaporation shortly preceding that at which gypsum is formed (Gulbrandsen and Reeser, 1969). The extent of the Big-horn Basin fluorite occurrence is not known, but the large size of many marine evaporite deposits would suggest the possibility of large low-grade new-type fluorite deposits.

SOUTH DAKOTA

Fluorite in minor amounts has been found in drill core from the Minnelusa Formation in the Pass Creek area, in Custer County. The mineral has also been identified in minor quantities in the Minnekahta Limestone about 25 miles (40 km) southwest of Custer (Roberts and Rapp, 1965).

Fluorite is reported as a gangue mineral in several gold mines of the northern Black Hills: Ross Hannibal, Ulster, Hardscrabble, Pennsylvania, Cutting, Boscobel, Double Standard, Hidden Treasure, and Homestake mines, Lawrence County. It occurs with autunite and limonite at the Davier mine (Roberts and Rapp, 1965). Some of the fluorite may be of Tertiary age and related to volcanism, as it impregnates rhyolite at the Hardscrabble mine.

NEVADA-WESTERN UTAH-SOUTHEASTERN OREGON-SOUTHEASTERN CALIFORNIA-WESTERN ARIZONA

By R. G. WORL and W. R. GRIFFITTS

The region made up of Nevada, western Utah, southeastern Oregon, southeastern California, and western Arizona contains numerous fluorspar deposits and fluorite occurrences. Most of the deposits are small, undeveloped, and poorly described, as compared to the numerous well-documented fluorspar deposits, many with substantial production, in Colorado, New Mexico, and trans-Pecos Texas. Nevertheless, this region contains three major fluorspar districts: Spor Mountain, Utah; Fluorine, Nev.; and Broken Hills, Nev., and one of intermediate size: Indian Peak Range (Cougar Spar and other mines), Utah (localities shown by Worl and others, 1974). Most fluorspar deposits in this region have been discovered and developed since 1935. Burchard in 1933 (p. 24) listed only four important fluorspar deposits in this region: the Castle Dome district, Arizona, the Fluorine district, Nevada, the Afton Canyon deposits, California, and the Silver Queen mine, Utah. Lindgren (1933b, p. 164) listed several fluorite gangue occurrences in this region, but very few of the now-known fluorspar deposits. In contrast, most of the known fluorspar districts in Colorado and New Mexico were listed by Lindgren (1933b, p. 165) or Burchard (1933, p. 24), suggesting that Colorado and New Mexico were more intensely prospected for fluorspar in the early days than were the States in this region.

Fluorspar in this region occurs in veins, mantos, and pipelike bodies in and associated with volcanic rocks, in

contact zones and stockworks of hypabyssal and plutonic intrusive rocks, in veins and mantos of indefinite association, in volcanoclastic sediments, and in pegmatites. Other potential fluorine resources are topaz-bearing volcanic rocks, and fluorapatite in replacement iron ore bodies.

Most fluorspar deposits in western Arizona and southeastern California are layered ("banded") and crustiform veins composed of fluorite, barite, black calcite, calcite, manganese oxides, and in places argentiferous galena, pyrite, and gold-bearing quartz. Fluorite is uncommonly the major mineral present. Most of these deposits are well-defined veins in nearly vertical fracture systems, although in the Bouse district, in the Trigo Mountains, and in the Harquahala Mountains, Ariz., fluorite, barite, calcite, and black calcite occur as breccia cement and space filling in small concordant tabular bodies in volcanic agglomerates and flows (Van Alstine and Moore, 1969). Most of the fluorspar veins are in rhyolitic to andesitic volcanic rocks, pelitic metamorphic rocks, and granitic plutonic rocks. Several have had small fluorspar production, less than 10,000 tons, whereas many have had considerable lead, silver, gold, and manganese-oxide production. Examples of deposits with appreciable metal and manganese oxide production are those in the Vulture Mountains, Harquahala Mountains (Snowball, etc. deposits), Trigo Mountains, and Castle Dome district, Arizona, and the Orocopia, Afton Canyon, Red Bluff, and Warm Springs deposits, California. The Castle Dome district, Yuma County, Ariz., is described in more detail in later pages.

In Nevada, Utah, and the Clark and Ivanpah Mountains, Calif., fluorspar veins and manto deposits are composed of fluorite, calcite, barite, quartz, and chalcedony and in a few places base- and precious-metal minerals. Layering and crustification are common and fluorite is generally the major mineral present. Most of these deposits are in volcanic rocks, rhyolite to andesite in composition, and in carbonate sedimentary rocks. Some are in granitic plutonic rocks.

Many of the deposits are believed related genetically to Tertiary volcanism although not all are layered-vein types occurring in volcanic rocks such as at the Baxter (Kaiser) mine in the Broken Hills district, Nevada, to be described in later pages. Other examples of volcanic-related deposits, lying in Horton's (1961, p. 8) "western epithermal fluorspar belt" in Nevada, occur in Pershing, Churchill, Mineral, and Nye Counties. Similar deposits elsewhere in the region are in the Indian Peak Range (Cougar Spar and other mines), Utah, and Wah Wah Mountains, Utah. Some deposits are similar to volcanic-related types but lack evidence of volcanic connections; these occur in eastern Nevada and in the Clark and Ivanpah Mountains, Calif.

Several major structural zones appear to have localized fluorspar deposits in the region. The "western epithermal

fluorspar belt" of Horton (1961) is a vaguely defined structural zone. Its northerly trend, about 50 miles (80 km) wide and 200 miles (320 km) long, through western Nevada is defined partly by the dominant northerly orientation of ranges in this part of the Basin-Range province. Other significant structures appear to have been more important in localizing districts, however, and these extend out of the western belt and have controlled localization of other districts in central and southeastern Nevada. For example, the Boulder Hill mine and Mount Montgomery Pass district in western Nevada and the Fluorine district and Nipton deposit in southern Nevada lie within the prominent northwesterly oriented Walker Lane structural zone. Similarly, farther north, the Broken Hills district, Union district, Quinn Canyon Range district, Lincoln mine, and Wells Cargo deposit lie along a northwesterly structural zone at the northeast edge of the Walker Lane. Deposits in eastern Nevada and western Utah are largely within two prominent northeast-trending structural belts, one extending from White Pine County, Nev., to the vicinity of Park City, Utah, and the other from Lincoln County, Nev., to the vicinity of Marysvale, Utah.

In western Arizona and southeastern California, fluorite deposits are largely restricted to a northwesterly structural zone that terminates near Phoenix. This area is conspicuous on the tectonic map of the United States because of the shortness and orientation of its northeast-trending mountain ranges, which contrast with the longer ranges having rather consistent northerly or northwesterly trends. Part of this aberrant structural grain probably resulted from the abundant, very young, northeasterly faults with right-lateral movement, of which the Garlock fault of California is an example, that may post-date the fluorspar mineralization. Part of the structure certainly is older than these faults and is part of the set of northwest-trending lineaments that are found through much of the Western Cordillera. This northwest-trending set of structures is perhaps related to the Texas lineament that is parallel to it and about 100 miles (160 km) north of it; the Texas lineament weakens northwestward as the southwestern Arizona lineament strengthens. The southwestern Arizona lineament may curve southward as it weakens, merging into north-trending structures that prevail near the Arizona-New Mexico State line.

Fluorspar occurs in carbonate rocks throughout the "western epithermal fluorspar belt" of Nevada (Horton, 1961, p. 6), in the Union district, Nevada, at several localities in White Pine County, Nev., at the Wells Cargo mine, Lincoln County, Nev., in the Clark Mountains, Calif., in the Star district, Utah, and in minor amounts in carbonate rocks at numerous other localities in these States. At most of these localities only veins have been recognized; replacement bodies as mantos along poorly defined fluorspar veins in carbonate sedimentary rocks

have been noted at the Wells Cargo mine, in the Clark Mountains (Crosby and Hoffman, 1951, p. 630), and in the Quinn Canyon Range, Nev. Fault-controlled replacement bodies in limestone are present in the Daisy mine, Fluorine district, Nevada (Cornwall and Kleinhampl, 1961, p. J20). The fluorspar deposits in the Quinn Canyon district, described below, are spatially related to intrusive rocks. Areas underlain by carbonate rocks containing either fluorspar veins or intrusives with high fluorine content should be excellent prospecting targets for large replacement bodies. Fluorspar replacement bodies may not be readily noticeable to the naked eye. For example, fine-grained fluorspar in replacement bodies at the Wells Cargo mine is similar in texture and color to unaltered limestone, and at some locations in the Clark Mountains, Calif., abundant sericite tends to mask the fluorite.

Fluorspar veins and mantos in this region are commonly in, or related to, Basin-Range bounding faults of Tertiary age and occur scattered along some fault systems, commonly as isolated pods.

Many of the deposits in the Nevada-western Utah-southeastern Oregon-southeastern California-western Arizona region have had minor production, less than 50,000 tons; the Indian Peak Range and nearby districts (Cougar Spar, Staats, and other mines), Utah, have produced more than 50,000 tons; the Spor Mountain district, Utah, has produced more than 100,000 tons; and the Fluorine district (which contains other deposits besides veins and mantos) and the Broken Hills district (Baxter mine), Nevada, have each produced more than 150,000 tons.

Pipelike fluorspar bodies are present at Spor Mountain, Utah (Staatz and Osterwald, 1959), and in the Fluorine district, Nevada (Cornwall and Kleinhampl, 1961). In both areas the bodies occur in fractured dolomite and are fault controlled. At Spor Mountain, described in more detail below, most of the fluorspar occurs in the pipes, veins being of minor importance. The pipes in the Fluorine district are part of a complex of fluorspar fissure veins, breccia zones, mantos, tabular replacement bodies, and pipelike bodies in dolomite which has been intruded by hypabyssal bodies of rhyolite. Fluorspar production and estimated reserves at Spor Mountain, all from the pipes, exceed 350,000 tons (Thurston and others, 1954, p. 48).

Three occurrences of fluorite in volcanoclastic sediments have been recorded: Spor Mountain, Utah (Staatz and Griffiths, 1961; Staatz, 1963), Honey Comb Hills, Utah (McAnulty and Levinson, 1964), and Rome, Oreg. (Sheppard and Gude, 1969). At Spor Mountain fluorite occurs in a water-laid tuff on the flats just west of the area of the fluorspar pipes described above. Microscopic fluorite occurs dispersed through altered tuff and in a fine-grained intergrowth with opal and chalcedony in nodules up to 12 inches in diameter. These nodules, probably replaced limestone pebbles and cobbles, are dispersed

through the altered tuff and make up several percent of large bodies of mineralized rock. X-ray analyses of 16 samples of altered tuff containing no large fluorspar nodules indicate an average of about 3 percent fluorite with a range from less than 1 percent to 8 percent fluorite (D. A. Lindsey, oral commun., 1971). The Honey Comb Hills deposits are similar to those at Spor Mountain but smaller in scale. Fluorite content of near-surface samples from the Honey Comb Hills averages 6.3 percent and is as much as 10 percent (McAnulty and Levinson, 1964, p. 773). Both the Honey Comb Hills and Spor Mountain deposits are thought to have formed from laterally spreading hydrothermal solutions (McAnulty and Levinson, 1964, p. 773; Staatz and Griffiths, 1961, p. 948-949). Both deposits contain anomalous amounts of beryllium. The Spor Mountain deposits, which constitute the World's largest known resource of beryllium, have been mined since 1969 for their beryllium content; fluorine is not being recovered at present (1973).

Near Rome, Oreg., fluorite occurs as submicroscopic, nearly spherical grains in tuff, tuffaceous mudstone, and mudstone of a lacustrine deposit of Tertiary age. Fluorite content is generally less than 5 percent, but is as much as 16 percent in some zones (Sheppard and Gude, 1969, p. D69). According to Sheppard and Gude (1969, p. D69) the "fluorite probably formed during diagenesis in sediments that had been deposited in an alkaline, saline lake."

No fluorspar has been produced from any of the deposits in volcanoclastic sediments.

Several tactite bodies in the Nevada-western Utah-southeastern Oregon-southeastern California-western Arizona region, many mined for their tungsten content, contain appreciable fluorite. Examples are deposits in the Tushar and Mineral Ranges and Star district, Utah, the Tem Piute mine, Nevada, and the White Mountains, Calif. Fluorite was obtained as a byproduct of tungsten mining at the Tem Piute mine by treating tailings from the milling operations (Horton, 1961, p. 13).

Replacement iron ore deposits in the Iron Springs district, Iron County, Utah, contain fluorapatite. Although the fluorine content is less than 1 percent, fluorine was extracted in 1957 during the processing of this ore for its iron content. Similar deposits of magnetite containing fluorapatite occur in Nevada but tonnages are not large and fluorapatite contents are not high (Reeves and Kral, 1955; Shawe and others, 1962); fluorine was not recovered from these deposits.

Fluorine content of Tertiary igneous rocks, although too low to be considered as a potential resource, may indicate fluorine-rich zones worthy of exploration. Shawe (1966, p. C210, table 2) listed several areas in this region where Tertiary volcanics contain unusual amounts of fluorine. The rocks are porphyritic rhyolite and topaz-bearing rhyolite from hypabyssal bodies, rhyolite and topaz-bearing rhyolite flow rocks, and rhyolitic tuffs. The

fluorine content of these rocks ranges from 1,200 to 17,500 ppm (0.12 to 1.75 percent). Coats, Goss, and Radar (1963, p. 942, fig. 1) outlined several areas in this region where Cenozoic silicic volcanic rocks contain fluorine in the range of 1,000-5,000 ppm.

DESCRIPTIONS OF INDIVIDUAL DISTRICTS AND DEPOSITS

NEVADA

BROKEN HILLS

The Broken Hills fluorspar district is in the wedge-shaped northeastern part of Mineral County and is 70 miles (110 km) southeast of Fallon, the nearest railroad point.

All rocks exposed in the Broken Hills district are Tertiary volcanics, mainly rhyodacite to andesite flows, tuffs, and breccias and rhyolite and quartz latite welded tuffs (Ross, 1961). Limestone beds that constitute a possible host for fluorspar deposits are present in the dominantly volcanic Excelsior Formation of Triassic(?) age just west of the district. The district is cut by a series of northeast- to north-trending faults, most of which have accompanying zones of hydrothermal alteration. Few, however, have been mineralized with fluorite, and only one fault zone is significantly mineralized.

For more detailed descriptions of the district see Thurston (1946), Matson and Trengove (1957), Ross (1961), and Archbold (1966).

One mine, the Baxter or Kaiser, has yielded significant fluorspar, and the following discussion mainly concerns this mine. The Baxter mine was in almost continuous operation between 1928 and the time of its exhaustion in 1957, producing more than 200,000 tons of acid- and metallurgical-grade fluorspar (Archbold, 1966, p. 10). The mine is closed and is considered to be mined out (Horton, 1961, p. 14).

The volcanic rocks in the vicinity of the Baxter mine are strongly faulted, brecciated, silicified, and hydrothermally altered. Much of the wallrock is altered beyond recognition of its original composition. According to Archbold (1966, p. 12), "All the fluorite veins are in Tertiary rhyolite that unconformably overlies weakly metamorphosed sedimentary and volcanic rocks presumed to be of Mesozoic age. The rhyolite is overlain by Tertiary volcanic rocks of intermediate composition." Small amounts of unaltered porphyry (quartz monzonite?) can be found on some dumps of the Baxter mine. This porphyry may be from narrow dikes that Thurston (1946, p. 2) reported to be common in the area. Thurston (1946, p. 2) also reported that there is no apparent relation between these dikes and the fluorspar mineralization.

The fault zone that has been significantly mineralized is called the main vein; it strikes N. 40° E., dips an average of 50° northwesterly, and has numerous bifurcations which trend north to northeast. The fault zone bearing the main vein is undulating and pinches and swells within short

distances, varying in width from 2 feet (0.6 m) at places on the 400-level to 18 feet (5.5 m) at the surface.

The main vein is an aggregate of independent seams and masses of fluorspar 3 inches (7.5 cm) to 1 foot (30 cm) wide. From published descriptions the main vein apparently is made up of a series of connected lenticular pipelike bodies in the plane of the fault (fig. 18). Fluorspar did not extend far below the 700-level of the Baxter mine, and along much of the vein it did not extend below the 400-level. Ore mined near the surface averaged 5 feet (1.5 m) in width and was as much as 9 feet (2.7 m) in width. On the 300-level ore mined averaged 1.5 feet (0.5 m) in width and was as much as 5 feet (1.5 m) (Thurston, 1946, p. 3). Early mining was for ore containing more than 85 percent CaF_2 , and Thurston (1946) considered only material of this grade as ore. Kaiser Corporation's portion of the total production, on the other hand, averaged 46 percent CaF_2 .

Fluorspar occurs as lenses, veinlets, and breccia cement within the fault zone. Layering and crustification with botryoidal and mammillary structures are normal. Judged from material left on the dumps, the fluorite was either a clear, pale-green or light-violet fibrous and columnar variety or a gray fine-grained variety intimately intergrown with chalcedony. Brecciated fluorite cemented by later fluorite or chalcedony is common, and slickensides along fluorspar seams are widespread. Intercalated with the fluorite are layers of chalcedony and minor layers of manganese oxide and "mountain leather," a fibrous mineral reported by Thurston (1946, p. 3) to be a member of the palygorskite group.

Laser probe analyses of pure fluorite from the Baxter mine show only trace amounts of barium, manganese, and strontium common to almost all fluorite. Veinlets of brown chalcedony in silicified and altered country rock and minor gray breccias in the fluorspar contain trace amounts of zinc, arsenic, antimony, lead (up to 1,500

ppm), and silver (up to 30 ppm). Manganese oxides present in the fluorspar also contain trace amounts of lead and silver.

The Broken Hills mine, in the eastern part of the Broken Hills district, in addition to production of fluorspar, has had minor production of silver and lead that came from quartz-filled fissure veins and stockwork lenses in volcanic rocks (Ross, 1961, p. 81).

QUINN CANYON RANGE

Fluorite occurs at several locations in the Quinn Canyon Range, Lincoln and Nye Counties (fig. 19). Past production of fluorspar has been small, 200 tons from the Rainbow prospect in 1945-46 and about 14 tons that contained 50 percent CaF_2 from the Nyco mine by Wah Chang Corp. prior to closure of the Tem Piute mill (Horton, 1961, p. 18). Two areas are currently (1972) being mined—the Steel property by Lee Fennison, Panaca, Nev., and the Mammoth property by the Adaven Mining Company. Both operators are trucking their ore to the mill at Caliente, Nev., 100 miles (160 km) to the east. For more detailed descriptions of the geology and mineral deposits of the Quinn Canyon Range see Sainsbury and Kleinhampl (1969).

In the Quinn Canyon Range fluorspar occurs in limestone and volcanic rocks in the vicinity of intrusive rocks. The deposits in the volcanic rocks are similar to the deposits in the Broken Hills district, Nevada, described above. The fluorspar deposits in limestone are diverse types of replacement bodies, fracture fillings, and veins characterized by presence of chalcedony and by layering.

Sedimentary rocks of early to middle Paleozoic age and tuffaceous sedimentary and volcanic rocks of Tertiary age make up the country rock of the Quinn Canyon Range (fig. 19). These rocks are intruded by a small hypabyssal quartz latite porphyry pluton in the south-central part of the area, by a medium- to coarse-grained granitic stock in

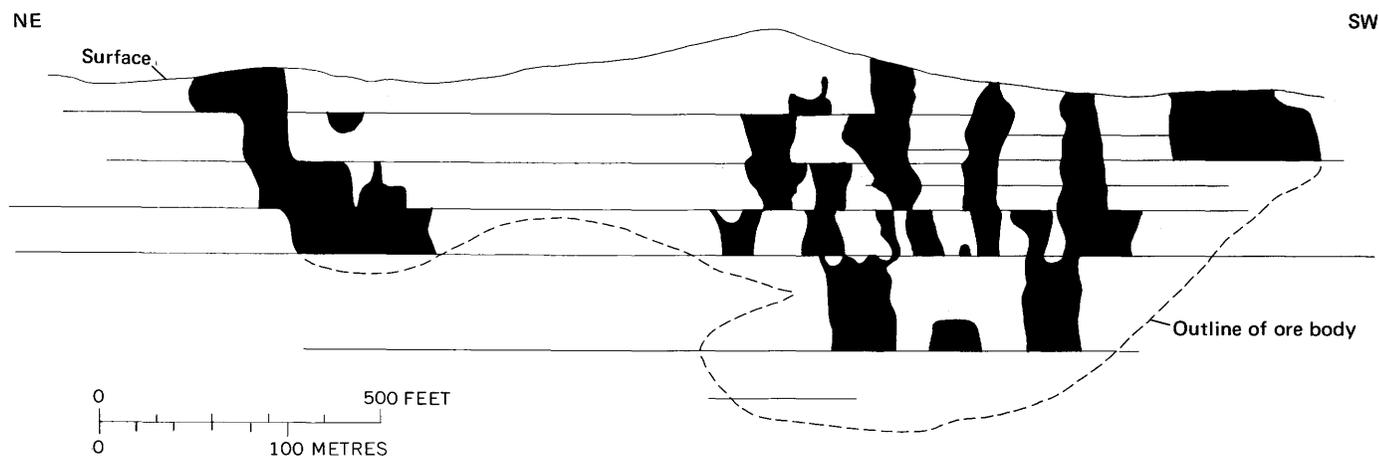


FIGURE 18.—Longitudinal projection along "main vein" of the Baxter (Kaiser) fluorspar mine, Broken Hills district, Nevada (from Matson and Trengove, 1957, fig. 4). Black indicates mined-out areas. Horizontal lines show mine levels.

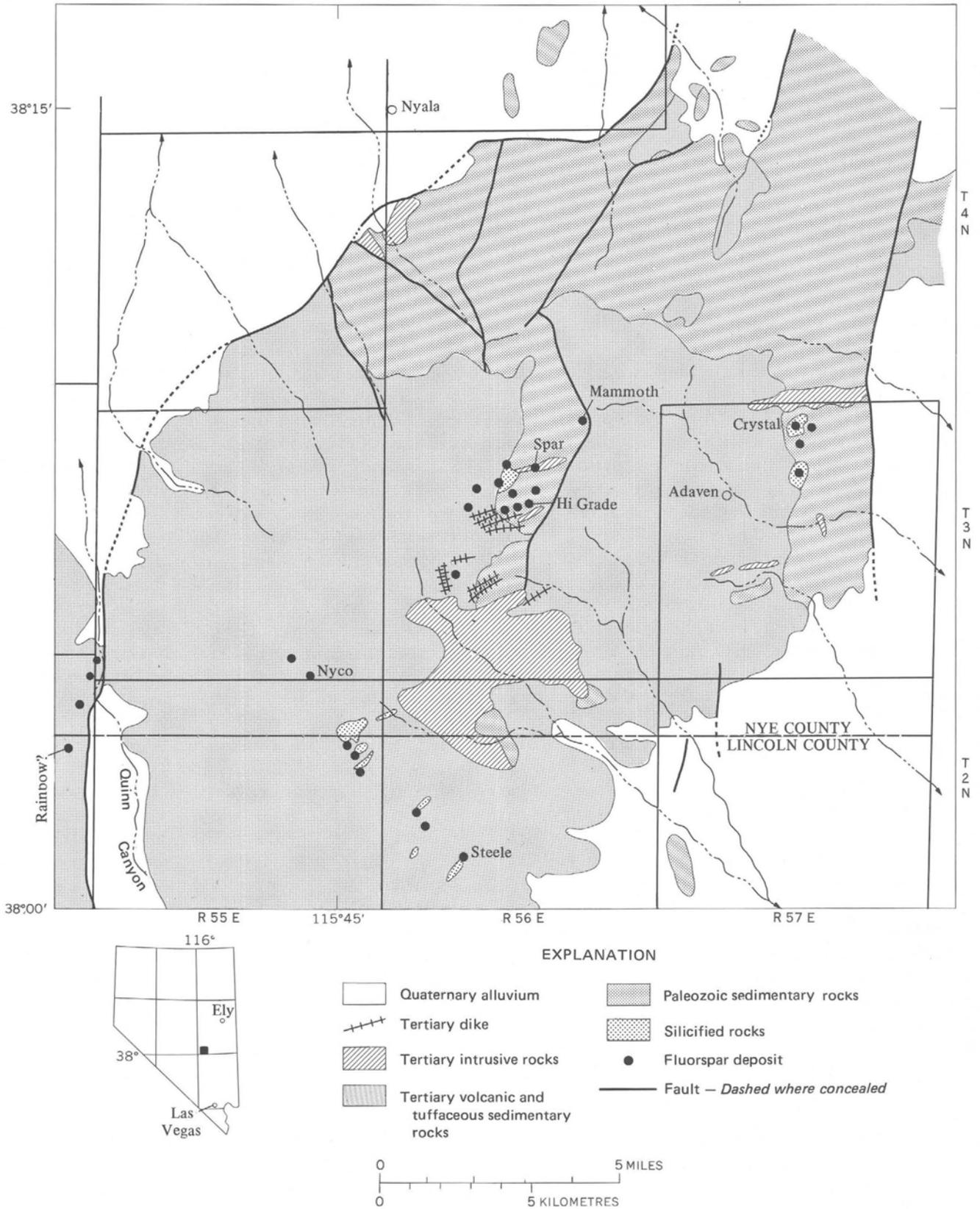


FIGURE 19.—Map of the Quinn Canyon Range, Nevada, showing locations of fluspar deposits (from Sainsbury and Kleinhampl, 1969, Pl. 1).

the north-central part of the area, and by numerous dikes and sills of fine- to medium-grained dacitic to rhyolitic porphyry and andesite (fig. 19) (Sainsbury and Kleinhampl, 1969, p. C3). The Paleozoic formations, composed mainly of limestone and dolomite, generally correlate with those assigned to the miogeosynclinal carbonate assemblage of the eastern Great Basin (Sainsbury and Kleinhampl, 1969, p. C3). The oldest Tertiary unit, of local extent only, consists of conglomerate and minor interbedded freshwater limestone. Volcanic rocks of Oligocene and Miocene age cover an extensive area of the Quinn Canyon Range (fig. 19). These rocks are rhyolite, rhyolitic to quartz latitic welded tuffs, and minor andesitic flows and breccias intercalated with some tuffaceous and sedimentary strata.

"Many of the mineral deposits are localized along the contacts of light-colored rhyolitic to dacitic porphyry dikes" (Sainsbury and Kleinhampl, 1969, p. C4). Wall-rock alteration consisted of silicification of the carbonate sedimentary rocks and silicification and pyritization of volcanic rocks. Several large altered zones are shown in figure 19. Not all these silicified zones contain fluorspar.

The Quinn Canyon Range is made up of several structural blocks bounded in part by Basin-Range faults. The structural blocks in which Paleozoic sedimentary rocks are exposed consist of gently folded or homoclinal sedimentary sequences cut by high-angle faults and, in some areas, thrust faults. The volcanic rocks are not as complex structurally but nevertheless probably overlie and conceal major structural units in the older rocks (Sainsbury and Kleinhampl, 1969, p. C4). The major dikes of the area trend east to northeast and cut across the strike of Paleozoic and Tertiary units and across the trend of thrust faults and folds. Discrete mineralized alteration zones in parts of the Quinn Canyon Range also trend east to northeast. The disparate trend and also the relatively late development of alteration, mineralization, and dike formation suggested to Sainsbury and Kleinhampl (1969, p. C6) that the fluorite deposits may be related to a late structural and igneous event, not yet clearly identifiable.

Fluorspar in the Quinn Canyon Range occurs in a variety of deposits. The following classification of fluorspar deposits in the Quinn Canyon Range is taken from Sainsbury and Kleinhampl (1969, p. C7). (Individual deposits mentioned are shown on fig. 19).

1. Relatively small but high-grade replacement deposits in limestone along dike walls (Spar claims).
2. Mixed fine-grained silica (jasperoid) and fluorite that have replaced shattered limestone and dolomite, commonly forming tabular, flat-lying deposits in which the bulk of the fluorite cements breccia fragments or coats vugs (Valley View and Bonanza claims, Crystal group). Some deposits are localized in shattered jasperoid zones along thrust faults (Jumbo and Horseshoe claims, Spar group).

3. Veins along fractures, in which fluorite and quartz form relatively coarse-grained intergrowths.
4. Irregular, relatively high-grade replacement deposits in limestone in which fluorite is intergrown with silica, both irregularly and rhythmically, to form layered ores ("coontail" or "banded" ores), as at the HiGrade and Mammoth deposits. Locally these replacement bodies are separated from or extend well out from dikes and are thus distinguishable from the other class of high-grade replacement deposits described under 1, above.

The deposits in volcanic rocks are less diverse, and only two main types are recognized: (1) well-defined fissure veins filled with nearly pure coarsely crystalline fluorite. These veins are bordered by argillized wallrocks containing noticeable to abundant disseminated pyrite (Nyc mine); (2) large tabular fluorite deposits. Fluorite occurs irregularly as discrete but discontinuous veins and veinlets, commonly intergrown with jasperoid, throughout large tabular strongly silicified zones and fractured zones in volcanic rocks. The rocks in the outer portions of the altered zones contain disseminated pyrite.

Fluorspar grade is related to type of deposit and type of fluorspar. A small breccia pipe, less than 50 feet (15 m) in diameter, on the Valley View claim of the Crystal group contains about 35 percent CaF_2 , all fluorspar occurring as breccia cement (Sainsbury and Kleinhampl, 1969, p. C11). At the Mammoth property, a large silicified zone in limestone—fine-grained siliceous "jasperoid"—contains 16–22 percent CaF_2 and 70–74 percent SiO_2 , whereas layered "coontail" ore contains 22–35 percent CaF_2 and 50–65 percent SiO_2 (Sainsbury and Kleinhampl, 1969, p. C13). Small fluorspar replacement bodies at the Spar group contain more than 90 percent CaF_2 (Sainsbury and Kleinhampl, 1969, p. C15). An area comprising about 28,000 ft^2 (2,600 m^2) on the HiGrade group contains approximately 65 percent fluorite, the richest zones containing about 75 percent. Another area, about 6,000 ft^2 (560 m^2) on the same group, contains by assay 72 percent CaF_2 (Sainsbury and Kleinhampl, 1969, p. C17). The HiGrade group consists of silicic replacement deposits in limestone and at least one shoot of layered "coontail" ore.

Mineralogy of the fluorspar deposits is simple: fluorite, quartz, jasperoid, and pyrite, and, in limestone replacement bodies, abundant calcite. Color and form of fluorite differ among different types of fluorite deposits. Fluorite in replacement bodies in limestone is either coarsely crystalline, nodular, and grayish white, or fine grained, compact, and light purple. The fluorite in large pure veins in volcanic rocks is mostly light green to colorless; the fluorite in the "coontail" ore and that cementing brecciated jasperoid is colorless or white, and the fluorite that forms small cubes is very faintly green (Sainsbury and Kleinhampl, 1969, p. C10).

UTAH
SPOR MOUNTAIN

The Spor Mountain fluorspar district, described in detail by Staatz and Osterwald (1959), is in the southwest part of the Thomas Range in central Juab County about 100 miles (160 km) southwest of Salt Lake City, Utah. Initial fluorspar production was in 1943, but large production did not occur until the late 1940's. More than 100,000 short tons of fluorspar was produced in the period 1943-56, (Staatz and Carr, 1964, p. 143). Following inactivity, the district recently (1971) has been revived as a result of the increased fluorspar market.

Exposed rocks range in age from Early Ordovician to Pleistocene. Most of the district is underlain by a thick sequence of apparently conformable rocks, chiefly carbonates, of Paleozoic age. Silurian and Ordovician dolomites are the chief fluorspar-bearing units. Tertiary volcanic rocks that locally overlie the Paleozoic rocks are latite, dacitic tuff, quartz latite, volcanic breccia, lapilli tuff, quartz latite tuff, rhyolitic water-laid tuff, and topaz-bearing rhyolite. Dikes and plugs of breccia, rhyolite, and quartz latite intrude the Paleozoic rocks, commonly along faults. Gravels and marls of the Lake Bonneville Group were deposited during Pleistocene time in the region surrounding the Thomas Range.

The Spor Mountain fluorspar deposits, though occurring dominantly in Paleozoic sedimentary rocks, are arbitrarily classified as associated with Tertiary volcanic rocks because of evidence of genetic relation to the topaz-bearing rhyolite. Near the fluorspar deposits, very large beryllium-bearing deposits in Tertiary volcanoclastic rocks contain about 5 percent fluorite (Staatz, 1963; Shawe, 1968).

The Paleozoic sedimentary rocks and the volcanic rocks have been tilted and now strike northeast and dip northwest. These consistently dipping rocks are cut by hundreds of faults belonging to at least five sets: (1) northeast-trending thrusts; (2) northeast-trending normal and high-angle reverse faults; (3) northwest-trending faults; (4) east-trending faults; and (5) north-trending faults.

According to Staatz and Osterwald (1959, p. 1-2), "Fluorspar deposits are of three types: oval to irregular pipes, veins, and disseminated deposits. The pipes, which show considerable range in shape and size with depth, have produced more than 99 percent of the ore***. [They] show evidence of two chief types of structural control: faults and intrusive breccia bodies." Ore pipes formed mainly by replacement along shattered zones in dolomite or volcanic rocks.

The ore consists of 65-95 percent of fluorite with montmorillonite, dolomite, quartz, chert, calcite, and opal as impurities. The fluorspar closely resembles a brown, white, or purple clay and forms either pulverulent masses or boxworks. With depth the grade of the ore commonly decreases, and masses of montmorillonite, chert, or quartz and dolomite have been found in increasing abundance in some deposits.

The fluorspar ore contained 0.003-0.33 percent U, according to analyses of numerous samples, and uranium grade varied considerably from place to place.

Staatz and Osterwald (1959, p. 2) concluded that the fluorspar ore

formed from fluorine-rich fluids, containing minor amounts of uranium, which were derived from the magma that formed the topaz-rich rhyolites of the Thomas Range during the last stages of volcanism. These fluids rose along faults and replaced shattered zones in the dolomite. Introduced elements other than fluorine and uranium were probably obtained from rocks underlying the deposits.

ARIZONA
CASTLE DOME

The Castle Dome district lies along the southwestern edge of the Castle Dome Mountains, Yuma County, in the southwest corner of the Kofa Game Range, and is bounded on the west and south by the Yuma Proving Grounds. From the time of its organization in 1863 until 1949 the district produced 17,726,937 pounds of lead and 459,321 ounces of silver, mostly during the early part of the period. According to Wilson (1933, p. 87):

The first important mining of fluorspar, which is a plentiful gangue mineral at Castle Dome, began in 1902. During 1902, 1903, 1904, 1908, 1909, and 1913 carefully hand-sorted crystals and pure screening from the De Luce claims were shipped to the Riverside Portland Cement Company's plant at Riverside, California, to be used as a flux in producing cement clinker.

The area was also active during World War I; fluorspar production from the district in 1902-17 exceeded 1,000 tons (Wilson, 1950). Since then production has been small and intermittent. For detailed descriptions of the district see Wilson (1933; 1951).

Country rocks in the Castle Dome district are well-bedded, weakly metamorphosed shale of probable Cretaceous age and diorite porphyry of Cretaceous(?) age (Wilson, 1951, p. 99). The shale rests unconformably upon granite and is faulted against schist, both of probable Precambrian age (Wilson, 1951, p. 99). These lithologies make up only a small part of the Castle Dome Mountains, the major part being volcanic rocks of probable Tertiary age (Wilson, 1933, p. 81). This volcanic pile includes about 2,000 feet (600 m) of rhyolites, andesites, tuffs, and obsidians and in places is overlain by several hundred feet of Quaternary(?) basalt. Locally, hypabyssal bodies of rhyolite porphyry have intruded the extrusive rocks; the fluorspar deposits appear to be related to these. The Cretaceous sedimentary rocks, host for argentiferous galena-fluorite veins, are dominantly greenish-gray shales and impure cherty limestones. Wilson (1933, p. 80) also reported locally abundant maroon shales, fairly pure limestones, brown arkosic sandstones, quartzites and conglomerates. Crosscutting the Cretaceous sedimentary rocks is a remarkable and pervasive swarm of dikes of diorite and rhyolite composition. Wilson (1933, p. 82) indicated that the diorite dikes are older than the lavas and the rhyolite dikes are younger. Alteration consisted of the

development of sericite and pyrite metacrysts throughout the rhyolite porphyry and in the Cretaceous sedimentary rocks, and in diorite in contact with the rhyolite porphyry dikes.

Almost all structural elements in the Castle Dome district strike north to northwest. These include range-front faults and other faults, mineralized veins, the diorite and rhyolite dikes, and the folded Cretaceous sedimentary rocks. In the vicinity of the Castle Dome district the volcanics form a broad anticline plunging east.

Fluorspar in the Castle Dome district occurs in argentiferous galena-fluorite veins. Gold-quartz veins and silver-bearing manganese oxide veins are common in surrounding parts of the Castle Dome Mountains. The argentiferous galena-fluorite veins occupy north- to northwest-trending steeply dipping fault zones that cut the Cretaceous sedimentary rocks and the diorite and rhyolite porphyry dikes. Most mineralization occurred in altered zones around the rhyolite porphyry, and the veins are best developed where diorite porphyry makes up one or both of the vein walls. Although most are less than 5 feet (1.5 m) in width, veins as much as 12 feet (3.7 m) in width have been reported (Wilson, 1933, p. 83), and most veins are continuous for great lengths, some as much as 5,000 feet (1,500 m).

The argentiferous galena-fluorite veins are largely fissure fillings and cemented breccias in which layering and crustification of the gangue minerals are common. Gangue consists mainly of layers of coarsely crystalline varicolored fluorite, coarsely crystalline calcite, and black calcite that are cut by veins and veinlets of bladed to massive barite and chalcedony. Several veins in the district are composed entirely of the gangue minerals occurring as described above. Where present, galena forms sheetlike masses or irregular veinlike bodies in the fluorite or calcite. In places, veins consist of nearly solid masses of galena up to 8 feet (2.5 m) thick (Wilson, 1933, p. 83). Other vein minerals are hydrozincite, smithsonite, wulfenite, vanadinite, mimetite, aragonite, gypsum, anglesite, cerussite, and other lead oxides. Galena is the only sulfide mineral that has been noted. No silver minerals have been recognized even though the galena contains as much as 30 ounces silver per ton.

Fluorspar deposits like those at Castle Dome are characterized by coarsely crystalline fluorite of high purity. Silica contamination does not affect the quality of the mined product, although lead contamination might. Most of these deposits may be related to Tertiary volcanism and many appear to be physically restricted to the volcanic pile with which they are associated. However, in districts like Castle Dome the source of the mineralizing solutions evidently was much deeper than the surface volcanics, and ascent of these solutions was controlled by major regional structures. Although fluorite is considered to be a gangue mineral at Castle Dome, as it is in most deposits of this

type, it is plentiful enough to be considered as a source of fluorspar, either as the major product or as a coproduct.

OTHER DEPOSITS

Several fluorite, barite, and manganese oxide deposits occur in an east-northeast-trending zone along the southern end of the Harquahala Mountains, the northern end of the Big Horn Mountains, and through the Vulture Mountains. Production of fluorspar has been minor and mainly from the Snowball deposit in the Harquahala Mountains and from deposits in the eastern part of the Vulture Mountains (Van Alstine and Moore, 1969). Varying amounts of quartz, chalcedony, calcite, black calcite, barite, fluorite and manganese oxides are present in the deposits. Iron oxides, malachite, and trace amounts of gold are widespread. Layering, crustification, druses, and vugs characterize the deposits. Country rocks are granite, gneiss, schist, limestone, basalt, and volcanic agglomerate. The deposits are generally localized along northwest- or east-northeast-trending fracture systems as pods, short veins, and breccia fillings; deposits in basalt are made up of numerous stringers and pods spread through diffuse breccia zones. In the vicinity of the Snowball deposit, fluorite-rich deposits form horizontal layers consisting of cavity fillings and breccia cement in volcanic agglomerate. Two trench samples across a fluorspar breccia zone at the Snowball deposit indicate a grade of 72 percent CaF_2 across a width of 4 feet (1.2 m), and 36 percent CaF_2 across a width of 12 feet (3.7 m).

COLORADO-NEW MEXICO-WESTERN TEXAS-SOUTHEASTERN ARIZONA

By R. G. WORL, W. R. GRIFFITTS, and R. E. VAN ALSTINE

Fluorspar deposits are plentiful in Colorado and New Mexico, States that rank third and fourth, respectively, in total fluorspar production, following Illinois and Kentucky. Fluorspar production in Colorado began about 1873 in the Jamestown district, Boulder County, and near Evergreen, Jefferson County. Almost 90 percent of the subsequent production has come from six districts: Northgate (Steven, 1960), Jamestown (Goddard, 1946), Browns Canyon (Van Alstine, 1969), Poncha Springs (Van Alstine, 1964; Russell, 1947?; 1950), Wagon Wheel Gap (Van Alstine, 1964; Steven, 1968), and St. Peters Dome (Steven, 1949). Production has been intermittent in most districts and reached a peak in 1944 when 65,209 tons of concentrates was shipped. Total shipments of fluorspar from Colorado through 1970 have amounted to about 1.3 million tons, or about 10 percent of the fluorspar produced in the United States since records of production were started in 1880. Most of the concentrates have been shipped to the steel industry at Pueblo, Colo., to chemical, aluminum, and ceramic plants in other States; and to U.S. Government stockpiles. By 1963 shipments decreased to

less than 10,000 tons, and only the Jamestown district was active. During 1969 an enlarged Northgate mine and mill began operation and produced concentrates for a new pelletizing plant at Cowdrey, Colo.

The grade of Colorado deposits that have been worked ranges from about 20 percent to more than 75 percent CaF_2 ; most deposits were opened by underground workings, but some of the lower grade but larger ore bodies were mined in opencuts. Deposits are as much as 45 feet (14 m) thick and 2,600 feet (800 m) long in the Browns Canyon district, and opencuts on a vein zone in the Northgate district have been developed over a length of about 4,400 feet (1,350 m) (Steven, 1960, p. 395). Fluorspar is mined below a depth of 1,400 feet (430 m) in the Jamestown district.

Many other localities in Colorado have produced a little fluorspar, mostly from small veins (Cox, 1945). A pegmatite in the South Platte district, Jefferson County, yielded a little fluorspar as a byproduct of feldspar mining. Fluorite is present as a gangue mineral in various metaliferous deposits of gold, lead, zinc, tungsten, molybdenum, beryllium, and thorium (Van Alstine, 1964), and extensive mine dumps and piles of mill tailings, such as those with fluorite in and near the Cripple Creek district, represent a possible future source of fluorspar.

Topaz has not been an industrial product in Colorado or New Mexico, and most of the known deposits are too small or of too low grade to offer much promise. The mineral is a prominent component of hydrothermally altered rock in the molybdenum mines near Climax (Wallace and others, 1968) and Henderson (White and MacKenzie, 1973), Colo., and might thus become a byproduct of molybdenum mining at those or similar deposits in the region. The large tonnages of rock processed in the concentrators could yield significant amounts of topaz, even with a low content in the raw ore.

Fluorspar mining began in New Mexico in the early 1880's in the Burro Mountains and Gila districts. Production reached a peak in 1944 when 43,000 tons of fluorspar was marketed. Fluorspar has been produced in at least 10 counties of New Mexico, with a total yield of about 650,000 tons. Of the total, about one-third came from the Zuni Mountains district, Valencia County (Williams, 1966, p. 4), nearly half originated in Grants County, coming from deposits in the Burro Mountains district, the Gila district, and the Cooks Peak district, and most of the rest came from the Fluorite Ridge district, Luna County.

Most of the fluorspar deposits in Colorado, New Mexico, western Texas, and southeastern Arizona are of Oligocene or younger age—younger than the latitic and rhyodacitic rocks of the great Sierra Madre Occidental volcanic field that occupies much of western Mexico and extends northward into New Mexico.

General aspects of the types of fluorspar deposits in the region are discussed below. Fluorite-bearing deposits of

Precambrian age were formed in a plutonic environment and have as their most widespread representatives the fluoritic pegmatites of the Llano area, Texas, the Petaca and other districts of New Mexico, a broad area in Douglas, Teller, and Park Counties, Colo., and an area east of Laramie, Wyo. Most of the pegmatites contain rather coarse-grained purple, green, and pink or cream-colored fluorite in the inner parts of moderately well developed zones. Associated minerals are red microcline, gray quartz, plagioclase, a black mica or amphibole, topaz, beryl, and a variety of rare-earth minerals including yttrian fluorite. A carload of fluorspar was reported to have been shipped from pegmatites in Douglas County, Colo., as a byproduct of feldspar mining, and another carload was a byproduct of pegmatite mining operations in Wyoming, but the potential of pegmatitic fluorite deposits is small. The pegmatite deposits in the Petaca district, New Mexico, contain coarse green fluorite in their inner parts associated with pale microcline, plagioclase, and muscovite mica; the mica has been the main economic product. Rare-earth minerals, though present, are much less common than in the other fluoritic pegmatites.

Fluorite deposits of Laramide or early Tertiary age are less widespread than either the Precambrian or the Oligocene and younger Tertiary fluorite deposits. Laramide deposits apparently are restricted largely to the Front Range mineral belt in central Colorado, where the younger Tertiary fluorite deposits also are found.

Environments of formation, structures, textures of mineral assemblages, and accessory mineral and metal contents differ among deposits of different ages and among deposits within age groups. This diversity of type is not so pronounced if only the major districts are considered. The Jamestown, Colo., deposits of middle Tertiary age contain fine-grained fluorite associated with minerals of lead, silver, gold, copper, and uranium in stockworks, pipelike bodies, and mineralized breccia zones, and represent a mesothermal type of mineralization (Lovering and Goddard, 1950, p. 43, 64, 258). Similar fluorspar deposits and associated alkalic intrusives occur in the Eagle Mountains, Tex.; Gallinas Mountains, N. Mex.; Iron Mountain, N. Mex.; Bear Lodge Mountains, Wyo.; and the Little Rocky Mountains, Sweetgrass Hills, Judith Mountains, and South Moccasin Mountains, Mont.; and fluorite occurs in trace amounts in and around many calc-alkalic intrusives throughout the West. These deposits are found in many rock types, although deposits of significant size occur in limestone or in shattered granitic plutonic rocks. Fluorite-rich deposits at Iron Mountain, N. Mex., are tactites in the contact zones of small silicic intrusives.

Most other major districts in Colorado and New Mexico are of epithermal type and of later Tertiary age, commonly layered and crustified veins, but also mantos in sedimentary and volcanic rocks. They are localized by

geologically young steep faults and breccia zones in Tertiary volcanic rocks, Paleozoic and Mesozoic sedimentary rocks, and Precambrian silicic igneous and metamorphic rocks near the edges of uplifts or depressions. Most deposits of this type in Colorado are well-defined veins in plutonic and metamorphic rocks or in volcanic rocks, whereas those in New Mexico are commonly diffuse vein systems and mantos in calcareous country rocks, such as those at Sierra Cuchillo, described elsewhere in this report. Deposits in southeastern Arizona generally are veins in plutonic, metamorphic, or volcanic rocks. Deposits in Colorado include those in the Northgate, Browns Canyon, and St. Peters Dome fluor spar districts, and the deposits at Crystal, Dillon, Poncha Springs, and Wagon Wheel Gap. Notable deposits in New Mexico are those in the Gila, Burro Mountains, Anderson, Gold Hills, Steeple Rock, Sierra Caballos, Zuni Mountains, Fluorite Ridge, and Cooks Peak fluor spar districts, and deposits at Tonuco, Tortugas Mountain, Bishop Cap, and Sierra Cuchillo. In southeastern Arizona, similar deposits occur in the Tonto Basin, Aravaipa and Stanley areas, the Whetstone, Sierrita, and Chiricahua Mountains, and the Duncan and Copper Dome copper districts. Most formed at rather low temperatures and pressures near the earth's surface; warm or hot springs are associated with the deposits in some districts (Van Alstine, 1947, p. 461, 465). In the Browns Canyon and Poncha districts, Chaffee County, Colo., fluor spar deposits of late Tertiary age formed under near-surface hot-spring conditions from very dilute fluids (Van Alstine, 1969). Study of fluid inclusions indicates temperatures of deposition at about 119°-168°C. The heat and fluoride are regarded as volcanic contributions to the mineralizing fluid.

The epithermal fluor spar deposits are aggregates of fluorite, quartz, chalcedony, barite, and various minor components. Many contain pale-green or white fluorite in grains 1-5 inches (2.5-12.5 cm) long. Some of these are equant, but columnar or fibrous structures and successions of layers with different grain size, color, or structure are common. Most vein fluor spar shows slight to strong brecciation. Blocks of country rock and early fluor spar are cemented by late fluor spar or gangue minerals. Fine-grained fluor spar is present in large amounts in some districts in which coarse fluor spar also is found.

Several Tertiary deposits in New Mexico are epithermal replacement deposits in upper Paleozoic sedimentary rocks, and some in Texas are in Cretaceous limestone. The deposits in Cretaceous limestone in Texas (Gillerman, 1953; Underwood, 1963) are among the few in the Western United States that are bedding replacement deposits like those in the Illinois-Kentucky district.

Fluorite is dispersed in Tertiary granite and occurs with topaz in small open veins in the Mount Antero area, Colorado. Like the vuggy veins in the Precambrian Pikes

Peak Granite, these fissure deposits have yielded excellent crystals to mineral collectors but no industrially important fluorite or topaz.

The intrusive rocks at Jamestown, Colo., at Mount Antero, Colo., and at similar occurrences are not closely associated with volcanic rocks but they yield radiometric ages of about 35 m.y. and are thus nearly synchronous with the volcanism of the region; the intrusives may occupy deep parts of former (now eroded) volcanic vents. Even where deposits and volcanic rocks are widely separated, as at Northgate, Colo., and the Big Bend area of Texas, they nevertheless may be related genetically.

A general discussion of the structural and geologic controls of fluorine mineral deposits in this broad region follows; the discussion encompasses northern Mexico as well as Colorado, New Mexico, western Texas, and southeastern Arizona in order to provide a more comprehensive review of the environment of the deposits.

In the southern mountain region of Texas, New Mexico, southeastern Arizona and northern Mexico, the distribution of fluorite districts is related both to the great Sierra Madre Occidental volcanic field of Mexico and to regional tectonic features. Three major structures that are involved are (1) the Texas lineament, a belt of faults, folds, and intrusives which extends southeast from east-central Arizona, through El Paso and the Big Bend area to a terminus northeast of Monterrey, Mexico; (2) the Rio Grande trough, a series of structurally depressed basins that extends north from El Paso probably to the vicinity of Northgate, at the Colorado-Wyoming State line; and (3) a rather ill-defined zone of intense faulting that crosses the volcanic field in a northeast direction near the International boundary where the volcanic field enters southeastern Arizona.

The Texas lineament is a complex structure with a history of instability extending onward in time at least from the Carboniferous. A submerged Paleozoic uplift is indicated by the transgression of formations of Carboniferous age across much older formations. The zone was also important in late Mesozoic time, as the Lower Cretaceous formations of Mexico terminate abruptly northward along a hinge line that lay along the lineament in southern New Mexico. Early Tertiary deformation resulted in tight folds and thrust faults, which appear to be the dominant structures in the eastern third of the lineament between the Big Bend and Monterrey, and have been mapped northwestward in Mexico to the International boundary near southwestern New Mexico. West of the Big Bend, these compressional structures are best developed south of the Border but they have been mapped in western Texas. There is a marked contrast near El Paso, where east-trending compressional structures predominate south of the Rio Grande and north-trending fault blocks predominate in the Franklin Mountains north of the Rio Grande.

Superimposed upon these older folds and thrust faults are many high-angle faults which bound blocks of both sedimentary and volcanic rock that may be raised or dropped several hundreds or even thousands of feet. Many of these, like the older structures, trend northwest, parallel to the lineament as a whole. Block faulting is best developed north of the border and west of the Big Bend. The faults farther southeast are persistent both laterally and vertically, but the displacements are commonly only a few feet and seldom exceed 100 feet (30 m) (Temple and Grogan, 1963, p. 1041). The trends of these eastern fractures are less consistently northwest than are the western fractures, and most commonly are north-northeast, east-northeast, west-northwest, or north-northwest.

Small stocks and dikes of rhyolite are rather common in the lineament (as in the Sierra Blanca area) and are accompanied by intrusives of alkalic rocks between Sierra Blanca and the Big Bend.

Fluorite-bearing deposits are found along most of the length of the Texas lineament, and are most numerous or largest near the two ends. The deposits in Mexico, east of the Big Bend, form a rather coherent though widespread group. Temple and Grogan (1963, p. 1051-1052) succinctly summarized the regional history that followed deposition of the Georgetown Limestone in Early Cretaceous time:

1. Broad warping, development of joints, and development of an undulating surface with low relief determined by joint-controlled erosion.
2. Deposition of the Del Rio Clay in Late Cretaceous time, largely in depressions in the erosion surface.
3. Deposition of Buda Limestone and the Eagle Ford Shale.
4. Folding along northwest-trending axes and renewed jointing.
5. Block faulting, most prominent in the north-northwest-trending Boquillas Valley graben; intrusion of rhyolite and other siliceous rocks.
6. Widespread fluorite mineralization.

The Mexican fluorite deposits include crosscutting veins and mantos, or replacement deposits parallel to beds in limestone (Van Alstine and others, 1962). Both types are restricted to the Georgetown Limestone of Early Cretaceous age. The largest crosscutting veins are along contacts between rhyolite dikes and the limestone, or between segments of dikes and in the same structures as the dikes. The very large mineralized pipe at the Cuatro Palmas mine, Coahuila, lies in such a gap in a rhyolite dike (McAnulty and others, 1963, pl. 1). According to Temple and Grogan (1963) the vein deposits are largely in the upper part of the Georgetown Limestone, extending through a vertical range of several hundred feet. The mantos are found in the uppermost part of the George-

town Limestone. They are tabular in vertical section and are elongated parallel to joints in the limestone.

The same restriction of fluorite mineralization to the upper part of the Devils River Limestone (equivalent to Georgetown Limestone) is found in the quicksilver veins of the Terlingua district, Texas. Yates and Thompson (1959, p. 72) reported that the veins contain accessory fluorite only where the vein walls are Devils River Limestone. However, Gillerman (1953, p. 61-62) reported 800 feet of Georgetown Limestone in the fluorite district in the Eagle Mountains, Tex., but the best host rock is the Finlay Limestone, which is below the Georgetown Limestone and separated from it by the intervening Kiamichi Formation. The mineralizing solutions must have had access to the Georgetown Limestone inasmuch as the reefs in the Grayson Formation, still higher in the section, are mineralized. There is little mention of systematic exploration of the limestone below the Georgetown in other districts, although McAnulty and others (1963) showed several small fluorite deposits in the Aguachile area in Edwards Limestone and one in the Kiamichi Formation; and in section they showed the large Cuatro Palmas deposit to extend downward through the Edwards Limestone (1963, pls. 1, 2).

Farther northwest along the Texas lineament, formations of the Lower Cretaceous Series are poorly developed and are not known to contain fluorite. Toward the north, along the northwestern end of the Cretaceous Mexican geosyncline, owing to the change in sedimentary facies, the Georgetown Limestone is apparently absent from the stratigraphic section. Thus the only fluorite prospect reported by Albritton and Smith (1965) in the Quitman Mountains of Texas in this northern area is in rhyolite.

Between El Paso, Tex., and Silver City, N. Mex., the structural relations of the fluorite deposits are rather complex, as the deposits are influenced by fractures of the Rio Grande trench system as well as those of the Texas lineament and the northeasterly fracture system. Structure is simpler still farther to the northwest. There are two rather ill-defined northwest-trending belts of fluorite mineralization in this westernmost area, separated from one another by 12-25 miles (20-40 km) of barren ground consisting of gravel-filled basins and hills of volcanic rocks. In the northeastern belt, the most westerly deposits commonly strike northwest along faults that parallel the lineament. Similarly, most of the deposits in the western part of the southwestern branch of the Texas lineament are in the northwest-trending fractures that are so common in the lineament. Farther eastward along the northeastern belt north-trending fractures become prominent as controlling structures for the fluorite mineralization, reflecting the fracturing associated with the Rio Grande trough. Northeast- and east-trending veins also are present and probably resulted from left-lateral movement along the Texas lineament. The northeast-trending veins lie

mainly in the area between the Lordsburg and Silver City districts, New Mexico, an area in which fluorite deposits are particularly plentiful and several moderately large mines have been opened. Such enhancement of mineralization at intersections of structures is well known to geologists both on this regional scale and on a smaller scale, affecting individual ore bodies, as at the Burro Chief fluor spar mine, Burro Mountains, N. Mex., one of the largest mines in the northeastern belt.

Much farther south in Mexico, major fluor spar districts are also proximal to the Sierra Madre Occidental volcanic field, but they are restricted to regions in which the continuity of the volcanic rocks is broken by younger structures that bound the elongate areas of various rock units portrayed on geologic and tectonic maps of the Republic of Mexico. These areas are elongate in a northwesterly direction in east-central Durango, southwestern Zacatecas, and southwestern San Luis Potosi, and in a northerly direction in northern Guerrero. There is thus a southward persistence of the northwest-trending regional structures that are widespread in the Western United States; the structures in Mexico have controlled mineralization in a similar fashion. The fluor spar district in northern Guerrero is associated with high-angle faulting in a region of north-trending structures and at the south end of the great volcanic field. Situated as it is south of the northwest-trending transform fault zone, marked by recent volcanic rocks, this region may not be closely related structurally to the region farther north. The fluor spar district near Parral, southern Chihuahua, is in a rather small area of northeast-trending structures that lie athwart the northwest-trending structures that prevail regionally. The northeasterly trend at Parral is parallel to, and possibly similar in origin to, the broad structure that crosses the Sierra Madre volcanic field in and near southeastern Arizona.

The Rio Grande trough is a general term for a series of basins that begins abruptly at the edge of the Texas lineament at El Paso and extends northward probably to Wyoming. Although the name gives prominence to one north-trending series of basins, the tectonic unit that concerns us here includes a much broader group of north-trending fault-block mountains, with their intervening basins, the whole reflecting major vertical movements. This tectonic unit, its parts very likely related in time and origin, is about 100 miles (160 km) wide in southwestern New Mexico, narrows to about 50 miles (80 km) at the latitude of Albuquerque, N. Mex., and then broadens to about 100 miles (160 km) again north of Santa Fe. In Colorado the tectonic relations are more obscure, as the Rio Grande trough cuts across the volcanic field of the San Juan Mountains and strongly developed northwest-trending fault blocks of the Front Range farther northeast. The two largest basins at the southern end of the tectonic unit, the Tularosa Valley to the east and the

Jornada del Muerto to the west, die out northward. In part this termination resulted from displacement along faults in the set that passes northwest through the Guadalupe and southern Sacramento uplifts. As the San Andres Range dies out northward, the broader structural high of the Sacramento uplift east of the Tularosa Valley continues northward to join the southern end of the Sangre de Cristo Range. Fluorite deposits apparently are scarce along the eastern flank of the Tularosa Valley and the Sacramento uplift, but the deposit reported from Torrance County, N. Mex., is in the broad structural high that lies between the Sacramento uplift and the Sangre de Cristo Range.

A belt of north-trending faults, nearly 20 miles (30 km) wide, lies along the western side of this part of the Rio Grande valley and is the westernmost part of the broad tectonic system. Faults of this belt form the eastern boundary of the Black Range and the southwestern boundary of the San Mateo Mountains and are found throughout the length of the intervening Sierra Cuchillo south nearly to the Cooks Range. Fluorite deposits are widespread in this belt, especially in the part north of Hillsboro. Fluor spar has been mined in the Sierra Cuchillo from typical epithermal veins in volcanic rocks and from replacement deposits in limestone of Paleozoic age, some of which are mantos without silicate gangue minerals and some are bedding-controlled replacement deposits with silicate gangue minerals (pyrometasomatic deposits).

The northern part of the Rio Grande trough in Colorado is very complex structurally and has the basins in an en echelon series of northwest-trending fault blocks that make up the Front, northern Sangre de Cristo, Sawatch, Mosquito, and Gore Ranges, and the entire complex is crossed in a northeasterly direction by intrusives and ore deposits of the Colorado mineral belt. As at the south end of the trough in southern New Mexico, this intersection of tectonic units is the locus of a large number of fluorite deposits. Here also, high-angle faults have localized fluor spar deposits. The largest deposits are along the Arkansas River graben, at the faulted north end of the North Park basin, near caldera walls in the San Juan Mountains, and near northwest-trending breccia reef faults, as at Jamestown. Possible northwest-trending belts of deposits may reflect structural control by faults with that trend, or may reflect greater exposure of older geologic features that resulted from uplift along the faults.

The northeast-trending zone of intense faulting that crosses the Sierra Madre Occidental volcanic field near the International boundary is one of the major structures that influenced fluorite mineralization; it is both structurally complex and varied in its effects. It is rather sharply marked from the southwestern corner of New Mexico southwestward almost to Hermosillo, Sonora, Mexico, by the abrupt ends of segments of the volcanic field to the

south. North of this northeast-trending boundary the mountain ranges are rather short and commonly oriented north-northwesterly. Fluorite deposits have been found in this region on both sides of the International border. To the northeast, along the trend of the zone, there is much less evidence of faulting, but fluorite deposits are particularly abundant where this zone crosses the Texas lineament and the major structures related to the Rio Grande trough between Lordsburg and Silver City. Some of the fluorite-bearing veins in these places strike northeast, an orientation that is less common than the northwest orientation prevalent elsewhere in the southwestern United States.

The only important fluorspar district in New Mexico that is not in either the Rio Grande trough system or the Texas lineament is in the Zuni Mountains. This range is an upfolded and upfaulted block in which rocks of Precambrian age have been brought to the surface. It is elongated northwesterly and very likely is not closely related to other structures of the region, although a cluster of fluorspar deposits, the frontal fault of the Sacramento uplift, and a constriction in the main chain of basins of the Rio Grande trough in the Socorro area are on the southeast projection of the Zuni Mountain trend. The Zuni Mountains are part of a late Paleozoic high area; possibly their trend reflects the older structure.

Most of the fluorspar districts in Colorado, New Mexico, western Texas, and southeastern Arizona have been idle during the last 15 years, because of the low price paid for the commodity and the competition of foreign mines. Few deposits have been exhausted. With the increased prices of recent years, however, the known deposits will be reopened and new ore bodies will be found in most of the districts. The discovery in 1968 of a large deposit in the central Sierra Cuchillo, N. Mex., a range with very little earlier production, indicates that the minor districts cannot yet be disregarded as important sources of ore. Fluorspar is currently (early 1973) being mined in New Mexico in the Winkler anticline, Hidalgo County, and exploration in the State is under way in the Gila and Cooks Peak districts, in the Sierra Caballos, at Iron Mountain, at Holt and Whitewater Canyons, Catron County, and in the Bitter Creek area, Grant County.

Good possibilities exist for the discovery of large low-grade deposits of the replacement or manto type in sedimentary rocks in this region. Deposits of this type have been described in New Mexico and Texas. In New Mexico, various Paleozoic limestones are the host rock in the northern Sierra Caballos, Sierra County; the Magdalena Group of Pennsylvanian age is found at the Tortugas and Bishop Cap deposits, Dona Ana County, and at deposits in the Sierra Cuchillo, Sierra County (Rothrock and others, 1946). Fluorspar is in Permian sandstones and siltstones of the Yeso Formation in the Gallinas district, Lincoln County (Perhac and Heinrich, 1964) and accompanies

uranium minerals in the Todilto Limestone of Jurassic age near Grants, Valencia County. Lower and Upper Cretaceous limestones were replaced along three favorable horizons in the Eagle Mountains, Hudspeth County, Tex. (Gillerman, 1953) and in the Christmas Mountains-Corazones Peak district, Brewster County, Tex. (McAnulty, 1967). Large, low-grade fluorspar deposits may form in certain sedimentary materials, for Tweto and others (1970, p. C69-C74) have described the Hammer deposit, Summit County, Colo., where Tertiary colluvium was mineralized by hot springs and then was broken up and diffused by Pleistocene landslides to form disseminated deposits.

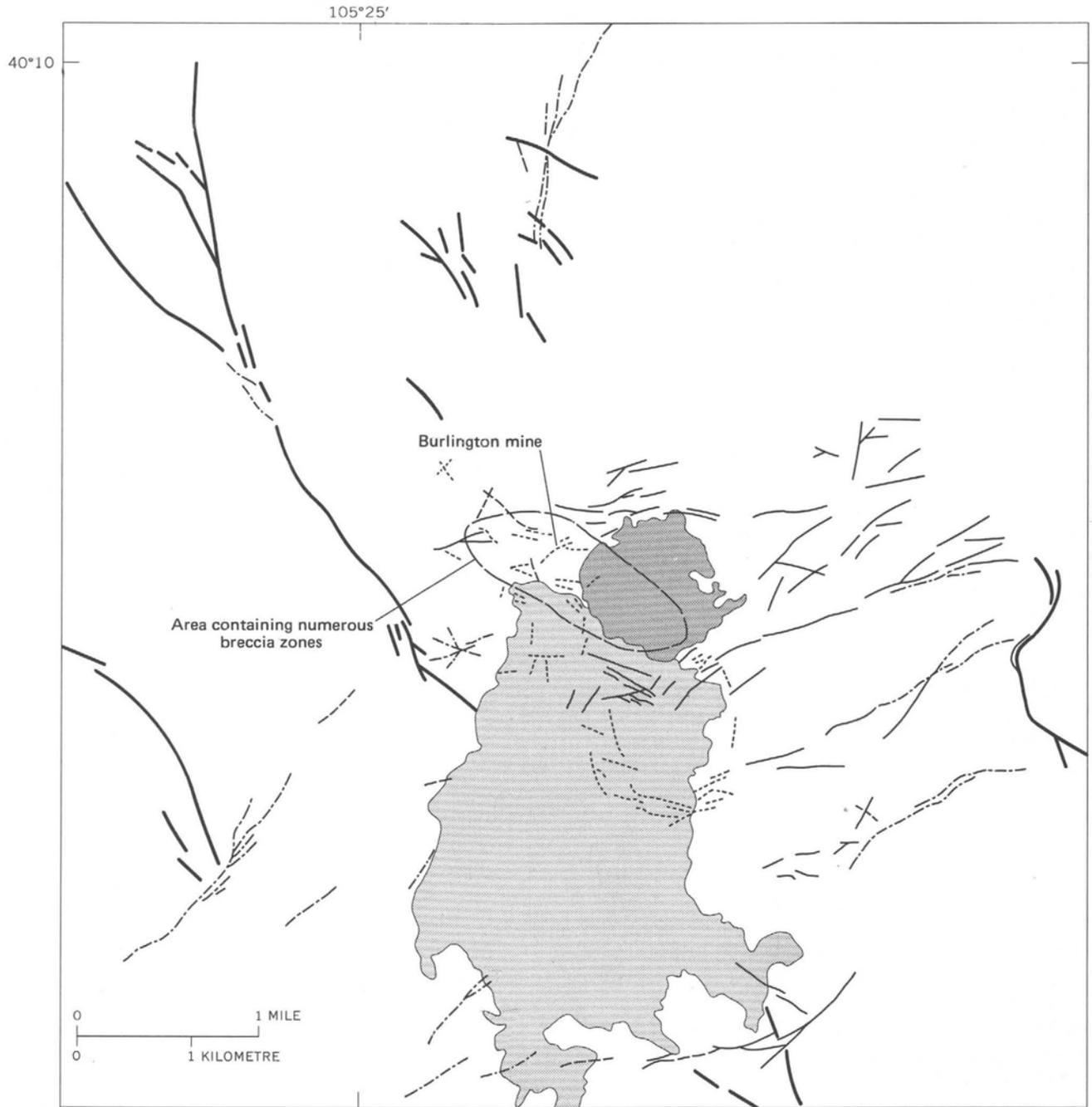
DESCRIPTIONS OF INDIVIDUAL DISTRICTS AND DEPOSITS

COLORADO

JAMESTOWN

The Jamestown, Colo., fluorspar deposits are in the Front Range, in the central part of Boulder County 17 miles (27 km) northwest of Boulder. Mining activity in the district began in 1874, and until 1940 the major commodities were gold, lead, and silver. Fluorspar was a byproduct of lead and silver mining as early as 1874, with the first appreciable production coming during the period 1903 to about 1920. In 1940 two companies, Allied Chemical Corporation and Harry Williamson and Son, began large-scale production of metallurgical- and acid-grade fluorspar. Allied Chemical Corporation's total production to 1972 of about 700,000 tons of acid-grade fluorspar (data published with permission) has been almost entirely from one mine, the Burlington, which has been in continuous operation since 1942. Harry Williamson and Son produced some fluorspar, mainly from the Emmett mine, and some from the Argo and Blue Jay mines, during 1940-56. All deposits in the district have been developed by underground workings, several to depths of 400 feet (120 m) or more; the Emmett mine, now closed, is developed to a depth of 1,000 feet (300 m) and the Burlington to a depth of 1,400 feet (430 m), the present (1972) lower working level. For detailed geologic descriptions of the district see Goddard (1946), Lovering and Goddard (1950), and Kelly and Goddard (1969).

Rock associations in the Jamestown district are characteristic of the Front Range, a Precambrian igneous and metamorphic complex containing numerous areas of high-level Laramide and middle Tertiary intrusions and related mineral deposits. The Precambrian rocks are Silver Plume Granite with scattered inclusions of metamorphic rocks, mainly biotite schist and hornblende gneiss (fig. 20). These rocks are intruded by a Laramide stock of hornblende granodiorite composition about 4 mi² (10 km²) in area, and a middle Tertiary stock of alkalic granite-quartz monzonite composition about 1 mi² (2.6 km²) in area (Goddard, 1946, p. 12). The alkalic stock, intruded at the



EXPLANATION

- | | | | |
|-----------|---------------------------|---|---|
| ----- | Argentiferous galena vein |  | Tertiary alkalic granite-quartz monzonite |
| ..... | Fluorspar vein |  | Tertiary granodiorite |
| ———— | Pyritic gold vein |  | Precambrian rocks |
| - - - - - | Gold telluride vein | | |
| ———— | Breccia reef | | |

FIGURE 20.—Jamestown district, Colorado (modified from Lovering and Goddard, 1950, fig. 77, and Goddard, 1946, pl. 1).

north end of the granodiorite stock, is a composite intrusive. Fluorspar deposits at Jamestown are related to this alkalic stock. Alkalic dikes are common in the district; they were intruded late in the igneous cycle and in places are younger than the fluorite (Goddard, 1946, p. 12). Fluorite is a common mineral in the alkalic granite-quartz monzonite and also occurs in crosscutting silicified zones within the stock. Zones in which all rock types were altered to clay minerals, sericite, chlorite, and carbonates are common, and extend beyond known mineralized zones. Similar altered rock is common in the contact zone of the alkalic stock. Country rock alteration was minor in the contact zone of the granodiorite stock.

Jamestown is at the northeastern end of the Colorado mineral belt, a northeast-trending zone in which Precambrian basement structures and Laramide structures controlled the location of Laramide and Tertiary intrusives and mineralization. This part of the Front Range is characterized by a series of strong northwest-trending faults, called breccia reefs, of Late Cretaceous age. These were important in the localization of ore deposits in several districts (Lovering and Goddard, 1950, p. 237). Two significant breccia reefs cut the Jamestown district just west of the major fluorspar deposits. They contain minor amounts of clear fluorite; at places in the district pyritic gold veins and gold telluride veins radiate from breccia reefs. Localization of the major fluorspar deposits, however, probably was controlled by fractures forming breccia zones different from the breccia reefs and created by the forceful intrusion of the alkalic stock (Goddard, 1946, p. 13); the deposits were not localized by the breccia reefs. Fluorspar bodies in the Jamestown district are localized mainly in breccia zones and fissures that form radiating and ring fracture zones around the alkalic stock; fluorspar bodies also occur in fractures of regional northeast and northwest sets.

The Jamestown mining district contains four types of mineral deposits characterized by argentiferous galena, by fluorspar, by pyritic gold, and by gold telluride; all are about the same age, and all are genetically related. Pitchblende is present in some deposits. Lovering and Goddard (1950, p. 260) pointed out a rough zonal arrangement of these deposits around the alkalic stock; the sequence of zones outward from the stock is argentiferous galena, fluorspar, pyritic gold, and gold telluride.

Argentiferous galena occurs mainly in massive pipelike bodies, broken blocks, and individual grains scattered through fluorspar-bearing breccia zones, but also it occurs as massive lenses and disseminated grains in fluorspar and pyritic gold veins.

Most of the fluorspar is found in veins and large breccia zones around the western and southern edges of the alkalic stock. Minor fluorite also occurs in most pyritic gold and gold telluride veins within 1 mile (1.6 km) of the alkalic stock. Several generations of fluorite formed in the James-

town district and most are separated by periods of brecciation.

Pyritic gold veins occur throughout the district and cut all rock types, including alkalic granite-quartz monzonite. They are best developed outside the fluorspar zone and as far as 2 miles (3 km) from the alkalic stock. In mines where both pyritic gold and gold telluride veins are present, the gold telluride veins are demonstrably younger (Goddard, 1946, p. 12).

Most gold telluride veins are 1.5–3 miles (2.5–5 km) from the alkalic stock. However, the Buena mine, mainly on gold telluride veins, is just outside the major fluorspar zone on the west side of the alkalic stock. Tellurides have been found in many fluorspar deposits and in pyritic gold veins. Gold telluride veins are not confined to the Jamestown district; they have wide distribution in the northeast part of the Colorado mineral belt (Kelly and Goddard, 1969).

The major fluorspar ore bodies are in breccia zones, best developed in Silver Plume Granite along the western contact of the alkalic stock. The breccia zones are hundreds of feet in diameter, irregular in shape, and not related to known fault structures. Fluorspar in the breccia zones occurs in nearly vertical pipelike bodies that in plan are irregular in shape but tend toward lenticular, and are 10–100 feet (3–30 m) wide and as much as 500 feet (150 m) long (fig. 21). In the Burlington mine a vertical exposure

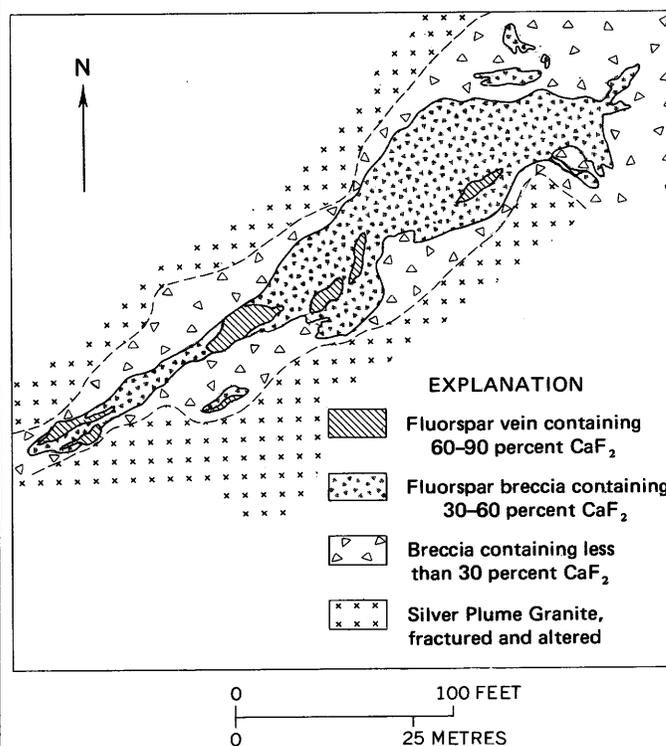


FIGURE 21.—Fluorspar deposit at the tunnel level of the Burlington mine, Jamestown district, Colorado (workings not shown). From Goddard (1946, pl. 8).

of one pipelike fluorspar body is more than 1,400 feet (420 m). Commonly the fluorspar ore bodies consist of a lenticular central core of a breccia composed of 60–90 percent CaF_2 and minor wallrock, surrounded by an irregular zone of fluorite-bearing breccia containing 5–60 percent CaF_2 (Goddard, 1946, p. 20). Large areas of breccia containing 5–30 percent CaF_2 are common. The fluorspar mineralized bodies are surrounded in most places by unmineralized but silicified breccia composed of altered wallrock.

Fluorspar veins several inches to 20 feet (6 m) wide and 150–1,000 feet (45–300 m) long are common around the southern and western edges of the alkalic stock, mostly in granodiorite. Goddard (1946, p. 20) reported that the veins commonly contain 60–85 percent CaF_2 .

Silica content of Jamestown fluorspar, especially of low-grade ore, is relatively high. A high-grade concentrate is readily obtained by flotation methods as the fluorite is generally not intimately intergrown with quartz or chalcedony. Most silica present is in wallrock fragments.

Many of the fluorspar ore bodies contain enough lead-, gold-, and silver-bearing sulfides to make saving of a sulfide concentrate potentially profitable. Goddard (1946, p. 20) reported two instances of Jamestown fluorspar yielding sulfide concentrates. At the Lehman mill in 1933 a galena-pyrite concentrate containing 30 percent lead and 0.28 ounce of gold and 3.6 ounces of silver to the ton was recovered from jigs and tables. At the Wano flotation mill in 1942 and 1943 a sulfide concentrate containing about 30 percent lead and 20–30 ounces of silver to the ton was recovered. Copper has also been recovered as a byproduct from Jamestown ore (Goddard, 1946, p. 20–21). Semiquantitative spectrographic analyses of 38 samples of fluorspar from the Burlington ore body, a pipelike body in a breccia zone, indicate an average of 33 ppm Ag, 3,700 ppm Pb, 4,850 ppm Ce, and 1,800 ppm Nd. Semiquantitative spectrographic analyses of 35 fluorspar samples from the rest of the district, mainly from veins, indicate an average of 9 ppm Ag, 2,600 ppm Pb, 1,150 ppm Ce, and 580 ppm Nd.

Fluorspar from breccia zones and veins alike is everywhere brecciated, and it exhibits at least two phases of fluorite and evidence of several events of brecciation. Generally the fluorspar ore consists of angular crystalline fluorite, sulfide fragments, and angular wallrock fragments, all less than an inch (2 cm) in diameter, set in a very fine grained matrix of rounded and corroded fluorite, clay minerals, carbonate minerals, and quartz. In breccia zones the fluorspar material is as described above, but it encloses large blocks of altered wallrock as much as several feet in diameter. Most of the fluorite is crystalline, light violet to dark purple, and is commonly zoned. Fluid-inclusion studies (J. T. Nash, oral commun., 1970) of fluorite from the Jamestown district indicate homogenization temperatures in the range 350°–400°C. Fluid salinities are

commonly high, 40 weight percent or more. Many fluid inclusions contain several “daughter” minerals. These data suggest that fluorite deposition took place from a hot, highly saline solution at high pressure. Pyrite, galena, sericite, and books of euhedral biotite, all fine grained, are disseminated through the fine-grained matrix. Sphalerite, chalcopyrite, tennantite, and enargite are locally present. Sulfides also occur as massive pipelike bodies in breccia zones and as massive lenses in veins. Chalcedony and hematite are locally present as a late breccia cement. Some low-grade fluorspar breccias contain abundant celestite, which also occurs with green fluorite in vugs. Ankerite, arfvedsonite, calcite, biotite, adularia, and purple fluorite crystals that display coarse-grained pegmatitic texture compose some fluorspar veins southwest of the alkalic stock. Minute grains of pitchblende have been identified in fluorspar from several deposits (Goddard, 1946, p. 19).

The Jamestown fluorspar deposits are characterized by fluorite crystals, both massive and granular, in aggregates intergrown with the other minerals. Conversely, columnar-fibrous fluorite, monomineralic layering, and crustification are not present. The depositional sequences were complex; more than one mineral phase was deposited from each hydrothermal surge, in contrast to the monomineralic depositional phases of low-temperature layered fluorspar deposits.

The alkalic magma was genetically related to, if not the ultimate source of, fluorine-bearing hydrothermal solutions that deposited the fluorite. The alkalic granite-quartz monzonite contains 0.05 to 2.3 percent F (average 0.27 percent) based upon analyses of 36 samples collected throughout the stock. Similar calc-alkalic or alkalic intrusives in receptive host rocks would be excellent exploration guides elsewhere, especially if they contained similar anomalous amounts of fluorine.

The potential of the Jamestown fluorspar deposits is enhanced by the presence of large areas of mineralized breccia, albeit low grade, and possible byproducts of lead, silver, gold, and of rare-earth elements that are present in the fluorite.

NORTHGATE

The Northgate fluorspar district lies in the northeastern end of the North Park intermontane basin near the Colorado-Wyoming boundary line. Walden, Jackson County, Colo., is 10 miles (16 km) south of the district and Laramie, Wyo., is about 50 miles (80 km) east. A major paved highway between Walden and Laramie (Colorado 127–Wyoming 230) passes through the district, as does a Union Pacific Railroad branch line originating in Laramie.

Although prospectors for copper noted veins in the district as early as 1900, no fluorspar claims were staked until 1918 and there was no recorded production until 1922. Colorado Fluorspar Corporation produced about 15,000 tons of metallurgical-grade fluorspar between 1922

and 1927 from the Fluorspar vein system. The district was then idle until 1941 when the Western Fluorspar Corporation leased the Colorado Fluorspar Corporation holdings, and a 450 ton-per-day capacity sink-float mill was constructed by Defense Plants Corporation. This operation ceased in 1945 after about 115,000 tons of fluorspar had been produced from underground and open-pit operations on both the Fluorine and Fluorspar vein systems. During this same period about 700 tons of fluorspar was mined from the Camp Creek mine on the northern end of the Fluorine vein system by Kramer Mines, Inc. In 1950 the Aluminum Company of America acquired the Camp Creek property, but to date (1972) has produced no fluorspar.

In 1951, Ozark-Mahoning Co. acquired control of most property on both vein systems, with the exception of the Camp Creek and Penber mines. Following construction of a 300-ton-per-day flotation concentrator in 1952, until operations ceased in 1959, Ozark-Mahoning produced fluorspar from three sources in the following proportions: 70 percent from open pit, 18 percent from sink-float tailings, and 12 percent from mine development. Ozark-Mahoning Co. expanded their Northgate facilities in 1968 to 650 tons per day capacity and also added a concentrate briquetting facility. Since this enlarged facility began operation, Ozark-Mahoning has been producing fluorspar from underground mine work along the Fluorspar vein system and from underground mine and open pit work along the Fluorine vein system. The following geologic description of the Northgate district is largely from Steven (1960).

Country rocks at Northgate are quartz monzonite and hornblende-biotite gneisses of Precambrian age; shales, sandstones and minor limestone of Mesozoic age; and arkose, tuffaceous siltstones and clays of the White River Formation of Oligocene age (Steven, 1960, p. 336). The bulk of the fluorspar occurs in veins within Precambrian quartz monzonite and within arkose of the White River Formation, and only minor fluorite occurs in faults in Mesozoic sedimentary rocks and in veins in Precambrian metamorphic rocks. Silicification and pyritization of the quartz-monzonite wallrock were common along the Fluorspar vein system, and argillization and silicification of the White River Formation were common along the Fluorine vein system.

The dominant structural feature of the district is the Independence Mountain fault, an east-trending and northward-dipping reverse fault with a hanging wall of Precambrian rocks and a footwall of Mesozoic sedimentary rocks. This fault, which predates the White River Formation (Steven, 1960, p. 369), transects earlier Laramide structures and forms the abrupt north boundary of the North Park intermontane basin.

Fluorspar occurs as veins in two parallel northwest-trending fault zones about 2 miles (3 km) apart that post-

date the White River Formation. These fault zones are in the hanging wall of the Independence Mountain fault. The western (Fluorspar) vein system extends slightly more than a mile (1.6 km) northwest from the Independence Mountain fault and is mineralized throughout most of its length; the eastern (Fluorine) vein system extends more than 2 miles (3 km) and is mineralized also along most of its length, though sparsely in places. Fluorite was deposited through a vertical range of more than 1,050 feet (320 m).

In the Fluorspar vein system fluorspar occurs as veins and veinlets a fraction of an inch to a few feet (millimetre to a metre) in width, as breccia "cement" coating breccia fragments, and as breccia fragments, all in coarse-textured fault breccia. Commonly, ore-grade fluorspar occurs in a zone, up to 20 feet (6 m) wide, of broken and cemented blocks of wallrock and fluorspar (breccia) containing veins of nearly pure fluorspar along or near one or both edges. Assays of samples of the fluorite stringers run as high as 97 percent CaF_2 (Steven, 1960, p. 399). The average for the vein zone for widths of 8-11 feet (2.4-3.4 m), however, runs between 40 and 50 percent CaF_2 , and the range is from 10 to 90 percent CaF_2 (Steven, 1960, p. 399).

Mineralogy of the fluorspar in the Fluorspar vein system is simple. Fluorite and chalcedony are the major minerals with some quartz and very minor barite, manganese oxides, and pyrite. Clay is common but is thought to be a weathering product of fine-grained fault gouge. Monomineralic layers ("bands"), crusts, and botryoidal layers with numerous drusy cavities are the characteristic forms of fluorite occurrence. Watercourses lined with fluorite are common. Columnar green fluorite, columnar honey-colored fluorite, crystalline purple fluorite, dense black fluorite, milky-white chalcedony, bladed barite, and manganese oxides occur in distinct layers where each layer is composed almost entirely of one mineral or form of mineral (fig. 22). A depositional sequence for the Fluorspar vein system is shown in the following table. Only the events marked "major" on the table occurred throughout the vein system; the others were of a local nature.

Depositional sequence of fluorspar in the Fluorspar vein system, Northgate, Colorado

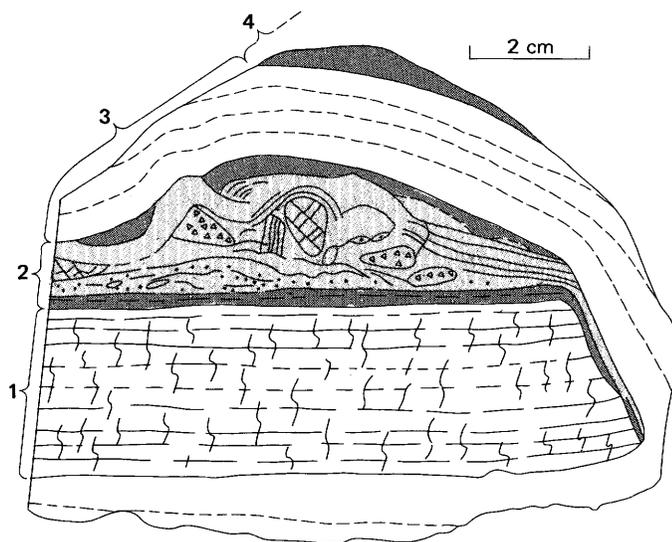
[Listed in order of increasing age. X, period of brecciation; m, major]

- Thin coatings of chalcedony, honey-colored columnar-fibrous fluorite, and manganese oxides.
- X Gray to black siliceous fluorite, mainly as a breccia cement. Contains stringers of pyrite. Part of the wallrock alteration occurred during this stage. (Major.)
- mX Honey-colored columnar-fibrous fluorite in veins and as breccia cement. (Major.)
- X Alternating bands of gray siliceous fine-grained fluorite, white chalcedony and small stringers of barite and manganese oxide.
- X Siliceous fine-grained breccia with some stringers of barite. (Occurs throughout, but in places is very minor.)

- mX Alternating bands of clear and purple crystalline fluorite, gray siliceous fluorite, and minor barite.
- X Gray siliceous breccia with stringers of pyrite. Mainly a dense black siliceous fluorite. Part of the wallrock alteration occurred during this stage. (Major.)
- mX X Columnar-fibrous green fluorite, white chalcedony, fine-grained gray siliceous fluorite, and gray siliceous breccia in alternating layers.

Fluid inclusion studies (J. T. Nash, oral commun., 1970) of fluorite from the Fluorspar vein indicated homogenization temperatures of 130°–175° and salinities of 0.1–3 weight percent. Fluid inclusions here are small and sparse. The data suggest that the mineralizing solution was a hot springs type consisting of predominantly meteoric water.

The Fluorine vein system is larger than the Fluorspar vein system and is as much as 70 feet (20 m) wide—but tends to be more diffuse and branching. The highest assays quoted by Warne (1947, p. 15–20) for sample widths of about 5 feet (1.5 m) are 70–80 percent CaF_2 . Mineralized rocks in the White River Formation contain about 30 percent CaF_2 for 15-foot (4.5-m) widths and between 20 and 25 percent CaF_2 for 35-foot (10.5-m) widths. Where quartz monzonite constitutes the wallrock, vein material averages about 45 percent CaF_2 for widths of 25–30 feet (7.5–9 m), and vein material averages about 30 percent CaF_2 for widths of 35–45 feet (10.5–14 m) (Warne, 1947, p. 15–20). In the Fluorine vein system most of the fluorspar



EXPLANATION

- 1 Layered columnar-fibrous green fluorite
- 2 Gray siliceous breccia with wallrock and fluorspar fragments and siliceous fluorite cement
- 3 Columnar-fibrous honey-colored fluorite
- 4 Gray fine-grained siliceous fluorite

FIGURE 22.—Slab of fluorspar from the Fluorspar vein system, Northgate, Colorado, showing different types of fluorite.

occurs as earthy masses and stringers in fine-grained fault breccia, and as fracture and space filling in arkosic beds of the White River Formation. Drusy cavities are common but massive veins of pure fluorite are not. The fluorspar consists mainly of fluorite and chalcedony with some quartz and manganese oxides. Montmorillonite, in many places intergrown or mixed with the fluorite and fault gouge, is common throughout, and crystalline calcite is common in mineralized arkose of the White River Formation.

Pure fluorite from both vein systems contains trace amounts of barium, manganese, strontium, and yttrium as do fluorites elsewhere. Laser probe analyses also indicate that trace amounts of zinc, copper, and silver occur in manganese-oxide zones, in scattered places in some fine-grained gray breccias, and in some minor columnar green fluorite layers. Molybdenum occurs in anomalous amounts in the wallrocks surrounding the Fluorspar vein and in places within the vein as described by R. G. Worl (U.S. Geol. Survey, 1970, p. A5). Ilsemannite, reported in parts of the Fluorspar vein system (Goldring, 1942), may be jarosite stained blue by molybdenum trioxide. The source of the molybdenum anomaly is molybdenite, widely disseminated through siliceous black material that is a submicroscopic intergrowth mainly of fluorite, chalcedony, and pyrite. This molybdenum-bearing material occurs as minor stringers and breccia fragments within the vein zone and as a pervasive stockwork of veinlets in the wallrocks around the fluorspar vein. The molybdenum-bearing material was the only vein material that penetrated the wallrocks away from major fractures.

The Northgate fluorspar district is not closely associated with Tertiary volcanic rocks, but such rocks are present in the region and probably the deposits formed during the episode of middle Tertiary volcanism that was responsible for the volcanic rocks of the region.

OTHER DEPOSITS

Fluoritic pegmatites of Colorado are in or near the Precambrian Pikes Peak batholith. Pikes Peak Granite contains 4,040 ppm fluorine (average of 38 samples; Fred Barker, written commun., 1972), much of it as fluorite. Although the total tonnage of fluorite in the batholith may be very large, the concentration of the mineral is so low that little, if any, will ever be recoverable. This dispersed fluorite increases the fluorine content of ground water, in places to objectionable levels, causing mottled teeth in the Colorado Springs area. The Pikes Peak Granite contains, in addition to feldspars, quartz, and biotite, small amounts of the cerium minerals allanite and bastnaesite. The Pikes Peak Granite locally also contains veins of quartz or of quartz and feldspar that contain crystals of topaz, fluorite, amazonite, or other minerals that are of value to mineral collectors but not to industry. The main economic importance of the veins and pegmatites is as indicators of mobile metal and fluorine

that somewhere in the area may be concentrated into minable deposits.

A Precambrian topaz-quartz-sillimanite gneiss in the central part of the Front Range, in Jefferson and Clear Creek Counties just west of Denver, contains major amounts of topaz. This unit, part of a high-grade metamorphic gneiss and granitic plutonic complex, is 11–100 feet (3.4–30 m) thick and crops out along strike for 7,000 feet (2,150 m). Three composite chip samples of this unit, taken by Sheridan, Taylor, and Marsh (1968, p. 3–6), contain 67, 23, and 36 weight percent topaz and, respectively, 4.2, 3.9, and 2.2 weight percent rutile. Modal analyses of four samples of the topaz-bearing gneiss indicate by volume 5.5–68.2 percent quartz, 30.1–71.9 percent topaz, 1.7–3.1 percent rutile, 18.2 percent sillimanite in one sample, 13.0 percent apatite in one sample, and trace amounts of zircon and muscovite. Rutile concentrates contain 0.05–0.15 percent Nb and 0.3–0.7 percent Fe as determined by semiquantitative spectrographic analyses. Sheridan, Taylor, and Marsh (1968, p. 7) suggested that the gneiss warrants investigation as an ore of rutile, especially because it might also yield a topaz or topaz-and-sillimanite product, which is salable as raw material for refractories and ceramics.

NEW MEXICO BURRO MOUNTAINS

The Burro Mountains district is in southwestern Grant County, 9–30 miles (14.5–48 km) southwest and south of Silver City. Fluorite was recognized in the mineral deposits in the area when mining of copper and turquoise began in the 1870's. Fluorspar was first mined there in the 1880's for use as flux in the copper smelters. More significant fluorspar mining began at the Burro Chief mine in 1913 and continued with interruptions until the 1950's. Information on the geology of the district was obtained from Gillerman (1953; 1964) and Rothrock, Johnson, and Hahn (1946).

The Burro Mountains are geologically complex. An uplifted fault-block mass of crystalline rocks of Precambrian age is intruded by dikes and stocks and overlain by volcanic rocks of Cretaceous and Tertiary age. The crystalline rocks were separated into four blocks by three persistent northwest-striking faults that may be elements of the Texas lineament. In the fluorspar areas these faults are accompanied by northeast- and east-trending cross-faults and north-trending splits of the main faults. The fluorite is found along these north-trending minor faults. One deposit is in volcanic rock and the others are in granite and schist; the deposits formed during the region's Tertiary volcanism. Precambrian granite is the most favorable host rock; hence the deposits are associated spatially with granite and temporally with volcanism.

The largest deposit, the Burro Chief, now within the Tyrone open-pit copper mine, is in a northeast-trending

breccia zone that is 10–100 feet (3–30 m) wide in granite. The deposit earlier had been opened by a shaft to a depth of 700 feet (210 m). Four types of ore have been distinguished: (1) high-grade massive vein fluorspar containing 75–90 percent CaF_2 ; (2) soft fluorspar breccia containing 35–75 percent CaF_2 ; (3) hard fluorspar breccia containing 50–90 percent CaF_2 ; and (4) breccia and other low-grade ore containing as much as 35 percent CaF_2 . Where unbrecciated, the fluorspar is clear, green, and moderately coarse grained. Clay and quartz are the most common impurities. The hard fluorspar breccia consists of an earlier variety with a green fluorite cement that is found in the upper part of the mine and of a later variety with a purple fluorite cement that is found throughout the ore zone.

GILA

The Gila fluorspar district in Grant County encompasses about 5 mi² (13 km²) along the Gila River 5 miles (8 km) upstream from the town of Gila. It was the locus of early fluorspar mining in New Mexico when the Foster mine was opened in the 1880's. Though small in area, the district has provided more than 47,000 tons of fluorspar (Williams, 1966). About 29,000 tons of this came from the Clum mine, the biggest producer during World War II.

The fluorspar deposits are in latitic and andesitic rocks of the Datil Formation of Tertiary age. The ore deposits were formed along faults and breccia zones, mainly as open-space fillings, and minor replacement of the volcanic rocks. The rocks were strongly argillized in some places and quartz was deposited with fluorspar in and near the veins. Most veins strike north to north-northwest. The Foster vein strikes northeast and the Cedar Hill, Clum East, and Green Spar veins strike northwest. Persistent northwest-striking faults separate the volcanic rocks from the younger unmineralized Gila Conglomerate farther southwest and cut the volcanic rocks northeast of the mining district. The ore deposits have not, in general, been completely delimited. The Clum North ore body was at least 510 feet (155 m) long, 150 feet (45 m) deep, and 6 feet (1.8 m) thick. The main ore body mined at the Foster mine was at least 280 feet (85 m) long, 130 feet (40 m) in vertical extent, and 3–8 feet (1–2.5 m) thick. The prospects for discovery of additional ore seem good. Mining may be prevented, however, if the canyon of the Gila River is flooded by a proposed dam.

COOKS PEAK-FLUORITE RIDGE

The Cooks Peak district in Luna County is about 30 miles (50 km) northeast of Deming. The district is credited with a production of 58,011 tons of which about 56,780 came from the White Eagle mine and the rest from four other deposits (Williams, 1966).

The district is underlain by a variety of rocks, including Precambrian granite, upper Paleozoic limestone, and Ter-

tiary volcanic rocks. These have all been cut by faults that strike northwest or north.

The White Eagle fluorspar deposits, like others in the Cooks Peak district, are in minor irregular, branching, brecciated, and overlapping fault zones of generally northwesterly trend (Rothrock and others, 1946, p. 98-102). The ore bodies have a total length of 850 feet (260 m) and have been mined through a vertical range of 175 feet (55 m). The veins are nearly all in Precambrian granite, but the western 100 feet (30 m) of one is in Tertiary rhyolite, and the fluorspar mineralization is believed to be related to the volcanic rocks. The fluorspar consists of white to pale-green fluorite with quartz and jasperoid impurities.

Fluorspar in the north part of the Cooks Peak district (which includes the Linda Vista deposit; Williams, 1966, p. 35) occurs as stringers, pods, and veins in slightly brecciated volcanic rocks. These fluorspar bodies are generally small, less than 5 feet (1.5 m) wide, but are numerous and sporadically distributed over a large area.

The Fluorite Ridge area in Luna County is near the southern end of the Cooks Range, about 15 miles (25 km) south of the Cooks Peak district and about 10 miles (15 km) north of Deming. The mining claims cover an area of nearly 1 m² (2.6 km²). Ten deposits are known in the district, which has yielded about 65,400 tons, 10 percent of the total of the State.

The district is underlain by sedimentary rocks of Paleozoic and Tertiary ages, and monzonite porphyry that intrudes them. All these rocks were cut by faults, basal dikes, and veins of fluorspar and quartz. The veins and dikes strike north to north-northeast. All but the deposits of the Tip Top and Hilltop Spar prospects are fissure veins, which are cavity fillings in limestone. The deposits have been most productive in broad breccia zones and at vein intersections. The veins contain coarse-grained pale-green fluorite and coarse- to fine-grained white, green, or red fluorite. Quartz and clay are the main gangue minerals.

SIERRA CUCHILLO

Fluorite has been found in many places in the northern 20 miles (30 km) of the Sierra Cuchillo in Sierra County, the part of the range extending south from Monticello Box to a point about east of Winston. In most places the fluorite is present only in small amounts, but fluorspar prospects have been opened and shipments have been made from a few of them.

Tactite deposits on Iron Mountain, Sierra County, have been known for many years and have been investigated as possible sources of iron, beryllium, tungsten, and fluorite (Jahns, 1944). The only ore shipped from the deposits has been fluorspar; less than 100 tons was shipped in the early 1950's. On the west side of Iron Mountain tactite replaces Carboniferous limestone that dips eastward into the

mountain. The rocks that are richest in valuable minerals are found only in certain beds and near silicic intrusive masses. Most of these beds are truncated at a shallow depth by a large mass of intrusive igneous rock. The total tonnage of valuable tactite therefore is much less than the extensive outcrops suggest.

The tactite contains many silicate minerals including the beryllium mineral helvite, and much scheelite and magnetite. Fluorite in dispersed small grains makes up 5-35 percent of parts of the silicated rock. In one area fluorspar forms irregular tabular layers several feet thick and a few tens of feet long that yielded the ore that was shipped. The fluorite constitutes at least 75 percent of these layers, as white translucent grains several inches across.

Several small fluorite-bearing veins in Tertiary volcanic rock have been prospected a few miles north of State Highway 52 and near the center of the Sierra Cuchillo. The fluorspar is moderately coarse grained, brecciated, and mixed with quartz, country rock, and calcite. None of the veins has been an economic source of fluorspar. The veins, together with fluorite in dry-wash sediments in this part of the range, attest to widespread fluorite mineralization; deposits of economic size and grade may be present in sedimentary rocks below the volcanic rocks.

The Victorio prospect is about 2 miles (3 km) east of Chise in the Sierra Cuchillo. It is a shallow shaft and several trenches opened in a vein that cuts limestone of Carboniferous age. The vein strikes N. 25° E. and is almost vertical. It consists of brown jasperoid, finely crystalline quartz, and fluorite and is 3-3.5 feet (about 1 m) thick.

The largest known fluorspar deposit in the Sierra Cuchillo was discovered in 1969 by Ira Young, of Winston, N. Mex. It is about 1 mile (1.5 km) south of the Victorio prospect and 2 miles (3 km) east-southeast of Chise. Fluorite has replaced several beds in limestone and forms mantos that dip gently to the west. The strike length of the mineralized beds exceeds 1,000 feet (300 m) and mineralized rock extends at least 500 feet (150 m) downdip. At the surface the total minable thickness of fluorspar is at least 20 feet (6 m), and some mantos are more than 5 feet (1.5 m) thick. The individual mantos are separated from one another by sufficient unmineralized limestone to require the mining of each manto separately. The mantos contain both coarsely crystalline white to pale-green fluorite and very fine grained friable white "sugar spar." Barite is uncommon. The most abundant impurity is unreplaced limestone.

The Ira Young deposit and the Victorio prospect are near the south ends of two major north-trending faults that occur in Canada Rancho de los Chivos and Montoya Canyon (Alminas and others, 1972). Fluorite can be found in concentrates panned from gravel from most tributaries

that drain into these valleys as well as from the two main valleys. The wide extent of the favorable limestone formation and of fluorite mineralization suggests that additional deposits may be found in the area.

ZUNI MOUNTAINS

The Zuni Mountains in Valencia County form a low ridge that extends about 50 miles (80 km) southeastward from the vicinity of Gallup. Fluorite was discovered in them in about 1908 and mining began in 1937. About 224,000 tons of fluorspar has been shipped.

The Zuni Mountains consist of a broad dome of Precambrian crystalline rocks and Permian sandstone and limestone flanked by Mesozoic sedimentary rocks (Goddard, 1966). The rocks of Precambrian and Permian ages are cut by many steep dip-slip faults that trend north-west. In most places such faults separate the Precambrian rocks from younger rocks. A persistent north-trending fault cuts the Precambrian rocks and offsets the northwest-trending faults. The northwest-trending faults are strongly silicified fracture zones that are stained red by fine-grained hematite. Fluorite is present in them in a few places.

The fluorspar veins in the Zuni Mountains are found in three groups, one near each end of the area of Precambrian rocks and one in its interior. All veins are within 1,000 feet (300 m) of northwest-trending faults. The veins strike northeast or east and are mineralized to depths as much as 800 feet (240 m) and through widths as great as 15 feet (4.5 m). They contain coarse-grained green and fine-grained purple fluorite; much of the ore is high-grade fluorspar containing 85–93 percent CaF_2 . Calcite, barite, and rare sphalerite, galena and chalcopyrite are accessory minerals. Three mines in the district have yielded important amounts of fluorspar. In addition to the mine worked to a depth of 800 feet (240 m) two were worked to depths of 350 and 600 feet (105 and 180 m), with no diminution of either size or grade in the veins.

SIERRA CABALLOS

Fluorspar deposits have been explored along a distance of about 20 miles (30 km) in the Sierra Caballos, Sierra County. The deposits are clustered into a northern group, near and north of Palomas Gap, and a southern group. The northern group has been most productive, providing about 25,000 tons of fluorspar; the Illinois and Independence or Blue Jacket mines yielded about 21,000 tons of this production (Williams, 1966).

The northern Sierra Caballos group of deposits is in an area of Precambrian granite and Paleozoic sedimentary rocks. The rocks were much faulted on the west side of the range, and open fractures and breccia zones formed, in which fluorite was deposited. The veins near Palomas Gap strike northeast and those farther north strike north-

west. The Illinois mine achieved its large production from three parallel veins, the Universal, the Oakland, and the White Star. They are mainly in Paleozoic sedimentary rocks (Johnston, 1928; Rothrock and others, 1946). The Oakland vein has been traced for 1,600 feet (500 m) and continues as a vein of quartz for an additional 600 feet (180 m). Fluorspar was mined along 350 feet (105 m) of the vein, with an average width of 11 feet (3.3 m) and average CaF_2 content of 50 percent. Barite and calcite are gangue minerals. The other two veins are shorter, but the Universal vein has been mined through a distance of 400 feet (120 m) and a vertical range of 200 feet (60 m). The average width was 9 feet (2.7 m) and the average CaF_2 content about 50 percent. The fine- to medium-grained white and pale-green fluorite is intergrown with calcite and quartz.

The Independence or Bluejacket mine was opened on a breccia zone that strikes N. 15°–20° W., between granite and sandstone. Fluorspar was mined from an open-cut about 100 feet (30 m) long. The ore, like that in the Illinois mine, contains quartz and minor amounts of barite.

Most fluorspar deposits in the southern group are on the west side of the Sierra Caballos and a few are on the east side. The total fluorspar production has been about 9,000 tons, of which 5,800 tons came from the Alamo (Nakaye) mine and 2,500 tons from the Lyda-K mine (Williams, 1966).

The Alamo or Nakaye mine was opened in fluorspar veins that strike northeast and northwest and occupy fractures in limestones of the Magdalena Group (Rothrock and others, 1946). The veins, opened by shafts and adits, contain brecciated limestone cemented by pale-green fluorite and calcite, as well as fluoritic fissure fillings. The Lyda-K mine exploits a fault-controlled vein in granite of Precambrian age; the vein is at least 2,000 feet (600 m) long. Recurrent fault movement has brecciated the early quartz-fluorite mixture, which was then cemented with purple fluorite. Shafts in the vein exposed it to a depth of 260 feet (80 m).

GRANTS

According to Peters (1958, p. 669–670), small bedded replacement deposits of fluorite are closely associated with uranium deposits in Jurassic limestone near Grants, N. Mex. "In some of the bodies, fluorite and calcite are the dominant minerals, with fine-grained uraninite incorporated in the fluorite crystals. The fluoritic uranium bodies lie within the Todilto limestone and locally within limestone lenses in the overlying shales of the Summerville formation." They are mostly in the upper half of the Todilto, which is generally about 15–25 feet (4.5–7.5 m) thick. According to Peters (1958, p. 669–670):

The fluorite bodies within the Todilto limestone are irregular in outline. Some of the bodies have no apparent structural control; others

exhibit a relation to the regional fold and fracture pattern. Some of the bodies have a tendency to follow the local joint pattern as mantos or as a linear series of tabular lenses. An association exists between broad gentle folds and some of the mineralized zones in that ore is most commonly found in crest or trough areas. A more direct association is noted in the occurrence of sharply broken and crumpled synclines within some of the orebodies.

SOUTHEASTERN ARIZONA

DUNCAN

Several fluor spar deposits occur on both sides of the State boundary between Arizona and New Mexico about 20 miles (30 km) northeast of Duncan, Ariz., in the foothills of the Mule Creek Mountains. There are two main groups of deposits: those in the vicinity of the Fourth of July mine, which is in Arizona in Daniels Camp, China Camp, and Goat Camp canyons, and those along Bitter Creek farther north, which are on the State line. The area around the Fourth of July mine is underlain by porphyritic and vesicular olivine basalt and fine-grained rhyolitic tuff intruded by dikes of rhyolite porphyry. The rocks are fractured and brecciated along northwest-trending zones. Fluor spar occurs as veins, pods, and stringers in brecciated zones. The fluor spar consists of coarsely crystalline green fluorite, dense milky quartz, and minor amounts of psilomelane. Quartz, chalcedonic quartz, and calcite stringers are common throughout fractured and brecciated basalt; fluorite, however, seems to be mainly along major northwest-trending fractures where it forms lenticular zones within quartz-rich veins (Trace, 1947). Total production of fluor spar from mines in Daniels Camp, China Camp, and Goat Camp canyons has been less than 8,000 tons CaF_2 , most came from the Fourth of July mine prior to 1946. Mined fluor spar shoots averaged about 3 feet (1 m) wide and 50 feet (15 m) long; the largest was about 400 feet (120 m) long. The fluor spar averaged about 65 percent CaF_2 and 25–30 percent silica (Wilson, 1950).

Fluor spar deposits near Bitter Creek are concentrated along or between the Steeple Rock and East Camp faults, which are parallel northwest-trending faults about 2 miles (3 km) apart and 14 miles (23 km) long (Gillerman, 1964, pl. 1). The faults separate a horst of predominantly dacitic volcanics of Tertiary age from younger Tertiary predominantly andesitic volcanics on either side. Small bodies of rhyolite intrude the other rock types. One mine, the Mohawk, which is in New Mexico, produced about 3,000 tons of fluor spar grading 65–70 percent CaF_2 prior to 1945 (Gillerman, 1964, p. 195). Fluor spar was found in pods, shoots, stringers, and disseminations in highly silicified breccia zones. Mined ore had widths as much as 7 feet (2.1 m), but average widths were less. Ore consisted of pale-green fluorite, quartz, pyrite, and blocks of highly silicified country rock. Much of the fluorite is massive and crystalline or columnar and occurs in layers with quartz; some is very fine grained and intimately intergrown with

chalcedonic quartz. Many fluor spar prospects in the vicinity of the Mohawk mine were originally gold or silver mines. Part of the Bitter Creek fluor spar area is the Steeple Rock mining district, New Mexico, where fluorite is a common gangue mineral in the gold and silver deposits that occur along the Steeple Rock and East Camp faults (Gillerman, 1964, p. 186).

OTHER DEPOSITS

The Lonestar mine at the eastern base of the Whetstone Mountains, Cochise County, ranks as Arizona's most productive fluor spar mine. During 1946–51 the grade of produced fluor spar was 85 percent CaF_2 ; silica content was 0.02–2.7 percent (Wilson, 1950). Coarse-grained green fluorite and quartz occur as layers in a northwest-trending fissure vein in Precambrian schist. Ore shoots average about 2 feet (0.6 m) wide, 25 feet (8 m) long, and 30 feet (9 m) high (Wilson, 1950).

Several small fluor spar deposits are located in the foothills east of the Tonto Basin post office, Gila County. Fluorite, quartz, muscovite, and clay minerals occur in narrow lenses, about 3 feet (1 m) in width, along fault zones in granite and granite gneiss. A bulk sample taken by the U.S. Bureau of Mines contained 72 percent CaF_2 , 20 percent silica, and trace amounts of gold, silver, barite, iron, and calcite (Cummings, 1946, p. 4). Tonto Mining and Milling Company was reported to be producing fluor spar from the area in 1972 (Guccione, 1972, p. 70).

CENTRAL AND EASTERN UNITED STATES

By A. V. HEYL and R. E. VAN ALSTINE

Fluorine deposits in the Central and Eastern United States vary widely in composition, size, and geologic type. Fluorine-enriched igneous rocks are common and widespread, and they consist mainly of granites, granodiorites, pegmatites, nepheline syenites, and mafic alkalic igneous rocks. Marginal varieties, considered magmatic by some, are nelsonite dikes composed of ilmenite and fluorapatite in central Virginia, and magnetite deposits that contain fluorite and fluorapatite at and near Iron Mountain, Mo.

High-temperature deposits enriched in fluorine occur in the Appalachian structural belt, in the Ozark dome of Missouri, and in the Llano uplift of Texas. They include four types:

1. Veins, lodes, and associated greisens that contain fluorite and topaz. These have been mined mainly for tungsten, tin, silver, lead, and gold. One group of deposits in Connecticut has produced a small quantity of fluorite.
2. Disseminations of fluorite and topaz, commonly associated with small veins and tactites. Scheelite, gold, and cassiterite are common associated minerals.

3. Complex skarns among which are iron and zinc deposits in the Precambrian of New Jersey, Pennsylvania, and southeastern and northern New York, that contain fluorite, fluorapatite, rare-earth fluocarboates, and in places abundant chondrodite, norbergite, and humite.
4. Fluorine-bearing tactites along granite and pegmatite contacts, and contact iron deposits next to Triassic diabase in Pennsylvania. Fluorite and topaz are the main fluorine-bearing minerals. Magnetite, scheelite, wolframite, molybdenite, helvite, chalcopyrite, garnet, and rare-earth and thorium minerals are associated with the fluorine minerals. One contact zone on Long Island, Maine, has yielded a small quantity of fluorite for apothecary shops.

Most deposits are veins which were formed at intermediate temperature. A few fluorite-quartz veins in the Cheshire County-Westmoreland district of southwestern New Hampshire have produced fluorspar. Complex fluorite-galena-sphalerite-quartz veins in the Faber, Va., area have also been productive. Other intermediate-temperature veins are silver-lead-copper-zinc-fluorspar-barite veins of the Connecticut Valley in Connecticut and Massachusetts and near Phoenixville, Pa. Somewhat more complex veins occur on Deer Isle, Maine, and at Thomaston Dam, Litchfield, Conn.

Most of the fluorspar deposits in the Central and Eastern parts of the United States are low-temperature veins, mantos, breccia bodies, stockworks, pipes, and disseminated deposits of several types of origin.

The most abundant deposits and some of the largest known economic concentrations of fluorspar are low-temperature vein and manto deposits in the Mississippi Valley and in the Appalachian Valley and Ridge province near related zinc deposits. Of these, the largest concentration of fluorspar in the Nation is in the Illinois-Kentucky district which contains Mississippi Valley-type (low-temperature vein and manto) deposits. Other Mississippi Valley-type deposits that have produced or may contain important resources are in the Central Tennessee district, the Cumberland River vein area, the Central Kentucky district, and the Rossie-Lowville, N. Y., area.

Appalachian Valley and Ridge province deposits are numerous and occur from Alabama to Pennsylvania (Van Alstine and Sweeney, 1968). Most of these deposits (Appalachian type) are irregularly shaped to blanketlike breccia bodies or are clusters of discontinuous veins, in both Cambrian and Ordovician carbonate rocks. A few deposits are fissure veins and disseminations in quartzite, shale, and carbonate rocks. By far the largest and potentially most important district in the Appalachian belt is the Sweetwater district in eastern Tennessee south of Knoxville. Farther east near the Tennessee-North

Carolina State boundary are the adjoining Del Rio, Tenn., district and similar Hot Springs, N. C., district; the former produced barite and a small quantity of fluorspar from breccia bodies, disseminations, and fissure veins in quartzite and crystalline rocks. A small tonnage has been produced from barite-fluorite breccia bodies that constitute the Gilley deposit in northeastern Alabama.

Disseminations of fluorite distributed widely in vugs and thin veinlets along with calcite, dolomite, barite, celestite, and sphalerite are found in central Pennsylvania, western New York along the south shore of Lake Ontario, northeastern Iowa, northwestern Ohio, and in the Serpent Mound cryptoexplosion structure in southeastern Ohio (Heyl, 1968). Such deposits may have been formed by simple warm connate brines or cold meteoric waters, or they may in places indicate undiscovered districts of the geologically more complex Mississippi Valley type or Appalachian type.

Residual or placer deposits derived from underlying bedrock deposits are known in a few places. Residual gravel spar deposits have been mined in western Kentucky, central Kentucky, and central Tennessee, but are unknown in the Appalachian region. The Streeter topaz placer in the Llano uplift of central Texas was described by Paige (1911), although a bedrock source has not been found.

Several of the districts and deposits in the Central and Eastern United States are described in more detail below, State by State, because of their resource potential or geologic interest. For each State, deposits with the greatest commercial potential are described first, followed by deposits of geologic interest, or of potential byproduct production of fluorite. Other possible fluorine sources such as apatite, rare-earth fluocarboates, and fluosilicates are described last.

ILLINOIS-KENTUCKY

ILLINOIS-KENTUCKY FLUORSPAR DISTRICT

By R. D. TRACE

More than three-fourths of the fluorspar produced in the United States has come from the Illinois-Kentucky district. Substantial quantities of zinc and some lead and barite also have been produced, mostly as a byproduct of fluorspar mining. The district is in Hardin and Pope Counties in southeasternmost Illinois, and adjacent Crittenden, Livingston, and Caldwell Counties of western Kentucky (fig. 23). Nearly all the mines are within the boundaries of 16 7½-minute quadrangles aggregating nearly 1,000 mi² (2,500 km²). The Illinois Geological Survey has published geologic maps of the Illinois part of the district, and the U.S. Geological Survey, in cooperation with the Kentucky Geological Survey, in 1972 has published geologic maps for most of the Kentucky quadrangles.

The earliest mining in the district was for lead at the Columbia mine, Crittenden County, Ky., in 1835 (Ulrich and Smith, 1905, p. 115). Lead mining started shortly thereafter in Illinois (Norwood, 1866, p. 366-372). From 1835 to the early 1870's, little fluorspar was mined. Only small amounts were produced from the early 1870's to about 1890, when an expanded market was created by the development of the basic open-hearth steel furnace in

which fluorspar was used for flux. Production since 1890 has been erratic but in general has risen. Production during World Wars I and II and the Korean conflict rose sharply, but in 1953-58, because of rising imports, production in the district decreased. Production has risen in recent years and probably will continue to increase in the near future. Production figures are summarized in the following table.

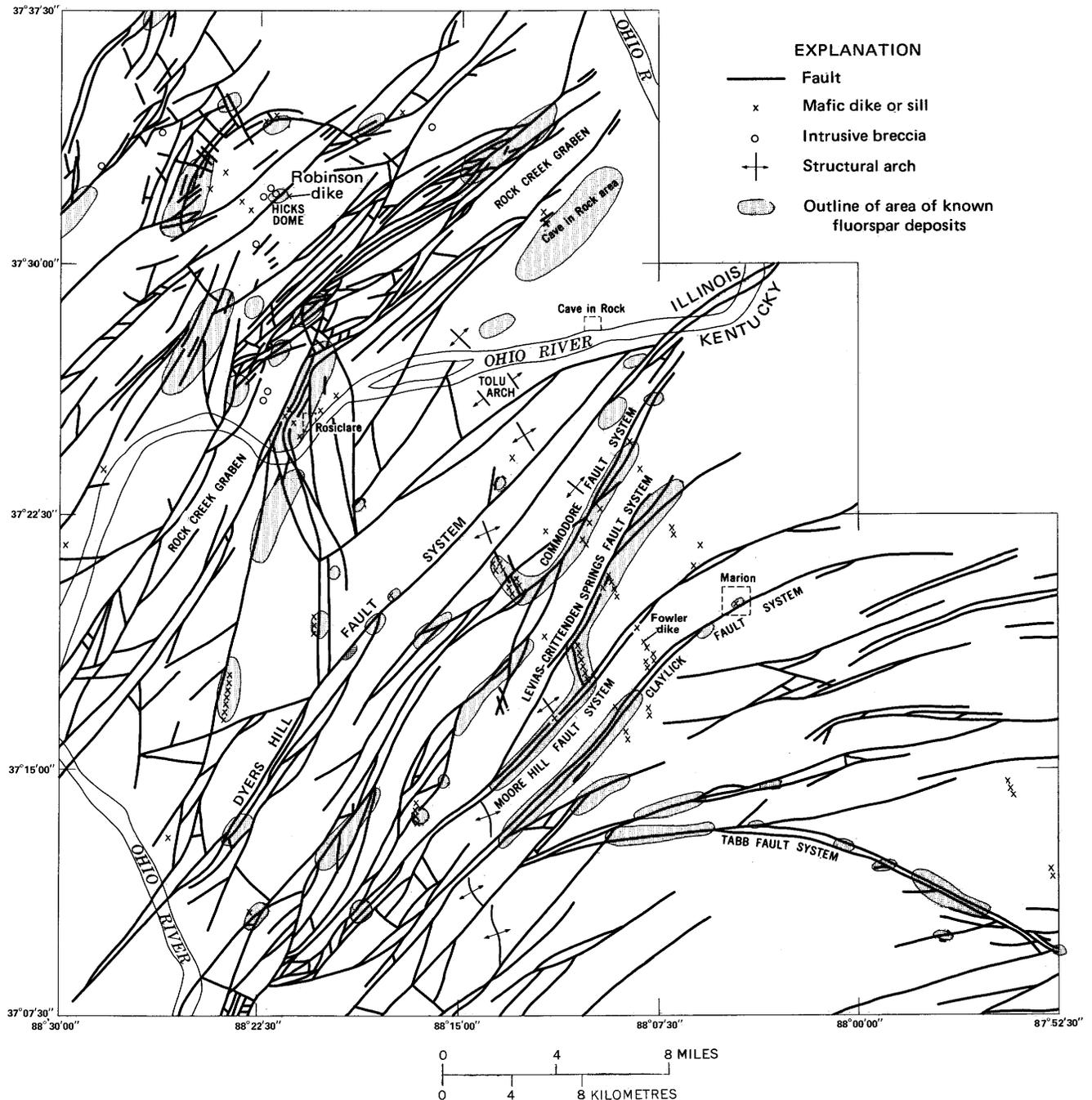


FIGURE 23.—Major structural features, igneous rocks, and distribution of known fluorspar deposits, Illinois-Kentucky fluorspar district. Compiled from published and unpublished geologic maps, 1962-72, by Illinois Geological Survey and U.S. Geological Survey.

Fluorspar production from Illinois and Kentucky
 [From U.S. Bur. Mines Minerals Yearbooks unless otherwise noted]

Years	Tons
Illinois	
Through 1963	6,163,345
1964	127,454
1965	159,140
1966	176,175
1967	210,207
1968	188,325
1969	88,480
1970	148,208
1971	1141,000
Total.....	7,402,334
Kentucky	
Through 1963	3,016,980
1964	38,214
1965	31,992
1966	28,725
1967	32,952
1968	17,050
1969	210,000
1970	25,000
Total.....	3,180,913

¹U.S. Bur. Mines estimate.
²Estimate by R. D. Trace.

Until the early 1930's almost the entire production was from vein ores. Since then, the amount of ore produced from bedding-replacement deposits near Cave in Rock, Ill., increased and so by the middle to late 1960's bedding-replacement ore probably constituted more of the Illinois production than did vein ore. The rise in the bedding-replacement to vein-ore ratio was in part due to the depletion of some of the large vein deposits near Rosiclare. Within the last few years the Illinois production from veins has increased and may soon equal the production from bedding-replacement deposits. In Kentucky, nearly all production has been from veins, although a substantial deposit of bedding-replacement ore near Joy has been known since the 1950's and was put into production in 1970 and was mined until 1973.

GEOLOGIC SETTING

Sedimentary formations that crop out in the district range in age mostly from Late Devonian through Early Pennsylvanian; where mining has been concentrated, the rock units at the surface are the Meramecian and Chesterian Series of Mississippian age. A small amount of unconsolidated Cretaceous and Tertiary sand, silt, clay, and gravel and Quaternary loess and alluvium is present locally.

The geologic column of exposed formations in the Illinois part of the district was summarized by Grogan and Bradbury (1968, fig. 2) (fig. 24). A slightly different column applicable only to the Kentucky part of the district is shown in figure 25. The lithologies in Illinois and Kentucky are generally similar but some differences in nomenclature are evident.

Most of the vein ores occur where the wallrocks are of either early Chesterian or late Meramecian age (early Chesterian and late Valmeyeran in fig. 24). The three principal bedded ore horizons also are either in the lower part of the Chesterian Series or in the upper part of the Meramecian Series.

Numerous intrusive mafic-alkalic dikes and a few sills are present in the district, and in addition in Illinois breccia forms dikelike or pluglike bodies (fig. 23). The mafic dikes and sills have been called mica-peridotites and lamprophyres; most are so highly altered as to defy precise classification. The dikes and sills are mostly dark gray to dark greenish gray, finely crystalline, and commonly porphyritic. They are composed mainly of dolomite, calcite, serpentine, chlorite, and generally phlogopitic biotite. Small quantities of magnetite, leucoxene, marcasite, fluorapatite, garnet, perovskite, and goethite are commonly present. Olivine and pyroxene are primary constituents but in a majority of the dikes these minerals mostly have been altered to serpentine (Clegg and Bradbury, 1956; Koenig, 1956; Trace, 1962b). Rarely, the mafic rocks are medium to coarsely crystalline (sample no. 197 in Zartman and other, 1967), light gray, and contain no chlorite or serpentine. Oesterling (1952, p. 324) described light-green dike material composed "nearly entirely of fine-grained calcite. The phlogopite has been completely replaced by calcite; there is no indication that olivine or pyroxene phenocrysts were ever present."

Chemical and semiquantitative spectrographic analyses of samples of the Illinois dikes and sills were reported by Bradbury (1962) and chemical analyses of samples of Kentucky rocks were given by Koenig (1956). The highly weathered Robinson dike near Hicks dome, Illinois, (Bradbury and others, 1955, p. 8) and similarly altered material from the Fowler dike in the east-central part of the Salem quadrangle, Kentucky (Trace, 1962a) were sampled in 1955. Semiquantitative spectrographic analyses of the samples showed that the Robinson dike contains much larger quantities of rare earths than does the Fowler dike (see fig. 23), as shown in the following table.

Semiquantitative spectrographic analyses of weathered mafic dikes, Illinois and Kentucky

[Analyses by Mona Frank, U.S. Geol. Survey, Sept. 1955]

Percent	Robinson dike (Near Hicks dome, Illinois)	Fowler dike (East-central part of Salem quadrangle, Kentucky)
>10	Si	Si
5-10	Fe Al	Fe Al
1-5	Ti Mg	Mg Ca
0.5-1	Ca K Na	Ti K
0.1-0.5	Ni Y Ba Ce	Ni Cr
0.05-0.1	Mn Nd	.....
0.01-0.05	La Sr V Co Cr Zr Cu	Mn Ba Na Sr V Cu
0.005-0.01	Nb Zn Ga	Co Ga
0.001-0.005	Yb Pb Mo Sc Be	La Nb Y Pb Nd Zr Mo Sc
0.0005-0.001 .....	.....	.....
0.0001-0.0005	Ag	Yb Ag Be

SYSTEM	SERIES	FORMATION	MEMBER	LITHOLOGY	THICKNESS (FT)	LITHOLOGIC DESCRIPTION	RANGE OF FLUORITE DEPOSITS	
							VEINS	BEDDED
PENNSYLVANIAN					600-900	Sandstone; shale; thin coals		
					0-80	Gray cherty limestone; shale		
MISSISSIPPIAN	CHESTERIAN	DEGONIA			0-30	Shale and thin-bedded sandstone		
		CLORE			100-120	Shale; limestone; thin-bedded sandstone		
		PALESTINE			50-60	Sandstone; silty shale		
		MENARD			100-130	Fine-grained limestone; shale		
		WALTERSBURG			15-50	Shale; shaly sandstone		
		VIENNA			10-20	Limestone; shaly limestone		
		TAR SPRINGS			90-110	Sandstone; shale; thin coal		
		GLEN DEAN			40-70	Fossiliferous partly oolitic limestone; shale		
		HARDINSBURG			90-115	Sandstone; shale		
		HANEY				Fossiliferous limestone		
	FRAILEYS			105-140	Shale; thin limestone			
	BEECH CREEK				Silty limestone			
	CYPRESS			80-110	Sandstone; shale			
	RIDENHOWER			25-65	Shale; shaly sandstone			
	BETHEL			80-100	Sandstone			
	DOWNEYS BLUFF			25-40	Crinoidal locally oolitic limestone			
	YANKEETOWN			30-45	Shale; siltstone (Yankeetown); limestone; shale (Shetterville)			
	VALMEYERAN	RENAULT	Shetterville		15-35	Light-colored oolitic limestone (Levias)		
		AUX VASES	Rosiclare		15-35	Calcareous sandstone, shale at base		
		STE. GENEVIEVE	Spar Mtn.		120-160	Light-colored largely oolitic limestone; sandstone lenses		
ST. LOUIS				350-400	Fine-grained cherty limestone			
VALMEYERAN	SALEM			500	Dark-colored, fine-grained limestone; foraminiferal calcarenite			
	ULLIN			125-360	Crinoidal, bryozoan limestone; dark-gray fine-grained limestone			
	FORT PAYNE			225-640	Siltstone; silty cherty limestone			
DEVONIAN-MISSISSIPPIAN	SPRINGVILLE				Gray and greenish-gray shale			
	NEW ALBANY GROUP			395	Gray to black shale			
DEVONIAN	LINGLE				Limestone and chert			
	GRAND TOWER			250	Limestone and chert			
	CLEAR CREEK				Limestone and chert			

FIGURE 24.—Stratigraphic column of exposed formations in the Illinois-Kentucky fluorspar district. From Grogan and Bradbury (1968, fig. 2).

SYSTEM	SERIES	FORMATION AND MEMBER	LITHOLOGY	THICKNESS, IN FEET	DESCRIPTION	
PENNSYLVANIAN				60-765	Sandstone; shale; thin coals	
	CHESTERIAN	Kinkaid Limestone		0-165	Limestone, sandstone, and shale	
Degonia Sandstone			5-38	Shale and sandstone		
Clore Limestone			70-125	Shale and limestone; thin sandstone		
Palestine Sandstone			30-75	Sandstone and shale		
Menard Limestone			80-145	Limestone and shale; thin sandstone locally		
Waltersburg Sandstone			20-60	Shale, siltstone, and sandstone		
Vienna Limestone			15-35	Limestone, cherty		
Tar Springs Sandstone			70-120	Sandstone and shale; thin coal locally		
Glen Dean Limestone			40-95	Limestone and shale		
Hardinsburg Sandstone			80-150	Sandstone and shale		
Golconda Formation			90-165	Shale and limestone; thin sandstone common		
Cypress Sandstone			45-140	Sandstone and shale; thin coal locally		
Paint Creek Formation			5-100	Shale, limestone, and sandstone		
Bethel Sandstone			20-120	Sandstone		
Renault Limestone			70-125	Limestone and shale		
MISSISSIPPIAN	Meramecian	Ste. Genevieve Limestone		200-300	Limestone, oolitic; thin sandstone	
		St. Louis Limestone	Upper member		250±	Limestone, cherty; containing <i>Lithostrotion</i> colonies
			Lower member		250-280	
		Salem Limestone		120±	Limestone, oolitic at top	
		Warsaw Limestone		230±	Limestone, large <i>Echinocrinus</i> spines at top	
		Osagean	Fort Payne Formation		600±	Limestone, mostly dark gray and very cherty or silty; locally upper part is light gray
DEVONIAN		Chattanooga Shale		Dark-gray shale		

FIGURE 25.—Generalized stratigraphic column of exposed formations in the western Kentucky fluorspar district.

In the last two decades, many more dikes and sills have been found principally because of the large amount of diamond drill exploration. A few new occurrences also have been found from surface mapping (Amos, 1966; Trace, 1966); mafic rock is difficult to find in surface outcrop, however, because a freshly exposed outcrop decomposes within a few years and becomes difficult to recognize. Also, the mafic rock material appears fresh and superficially resembles dark-gray limestones where exposures are continuously washed clean such as on Claylick Creek near the eastern edge of the Salem quadrangle (Trace, 1962a).

Numerous breccias and breccia "dikes" have been mapped in the Illinois part of the district (Baxter and Desborough, 1965; Baxter and others, 1967) and have been described in some detail (Clegg and Bradbury, 1956; Brown and others, 1954). According to Baxter and Desborough (1965, p. 287), "The breccias consist of angular to subrounded fragments of sedimentary, metamorphosed sedimentary, and igneous rocks in a matrix of finely ground rock and mineral fragments. The mineral fragments include quartz, pyroxene, augite, hornblende, apatite, mica, and feldspar." Grogan and Bradbury (1968, p. 376) identified fine-grained nepheline-feldspar rock in one of the breccias.

Many of these breccias are inferred to be pipes or small stocks, roughly circular or elliptical in plan and as much as 1,000 feet (300 m) in diameter. More commonly the breccias are vertical or steeply dipping dikelike bodies.

Unusual mineralization occurred in many of the breccias, both on the surface and to depths of over 2,000 feet (600 m) (Brown and others, 1954, p. 897-900; Heyl and others, 1965, p. B11; Bradbury, 1962, p. 6-8; Trace, 1960; Hall and Heyl, 1968). Minerals present are rare-earth-bearing fluorite, sphalerite, galena, barite, monazite, bertrandite, florencite, calcite, quartz, pyrite, brookite, yttrapatite(?), biotite, rutile, xenotime, apatite; beryllium, niobium, and zirconium are present in more than normal concentrations.

Until the early 1960's, the dikes, sills and breccias could be dated from stratigraphic relations only as post-Middle Pennsylvanian. In 1967 Zartman and others (p. 860-861) studied samples of biotite and hornblende from the dikes, sills, and breccias; on the basis of radio-isotope data they reported that "All the ages lie within experimental uncertainty of each other and give an average Early Permian age of 267 million years."

Wallrock alteration associated with vein deposits occurred along faults. Silicification of wallrock was the most striking change. Where Chesterian sandstone comprises the wallrock, sandstone close to or within the fault zone is extremely dense and commonly makes outcrops which are called "quartz reefs" or quartzite. Indeed, fragments of quartzite in places provide the only evidence of the surface trace of faults.

The alteration of limestone wallrocks generally was slight to moderate. In places numerous small doubly terminated quartz crystals and small masses of chalcedony have been reported where limestone is adjacent to a vein (Hardin, 1955, p. 24; Trace, 1962b, p. 17; Trace, 1954, p. 70). Fragments of dolomitic limestone, which is relatively common in the country rocks of the area, are present within the veins. No secondary dolomitization of the wallrocks of vein deposits has been reported.

Hall and Heyl (1968, p. 661) described visible wallrock alteration as much as 100 feet (30 m) laterally from bedding-replacement deposits. According to them, alteration included solution thinning of strata, silicification, dolomitization, and clay mineral alteration. Brecke (1962, p. 525-530) described the alteration of country rock, mostly within the mineralized zones, as decalcification, dolomitization, and silicification.

According to Heyl and Brock (1961, p. D3),

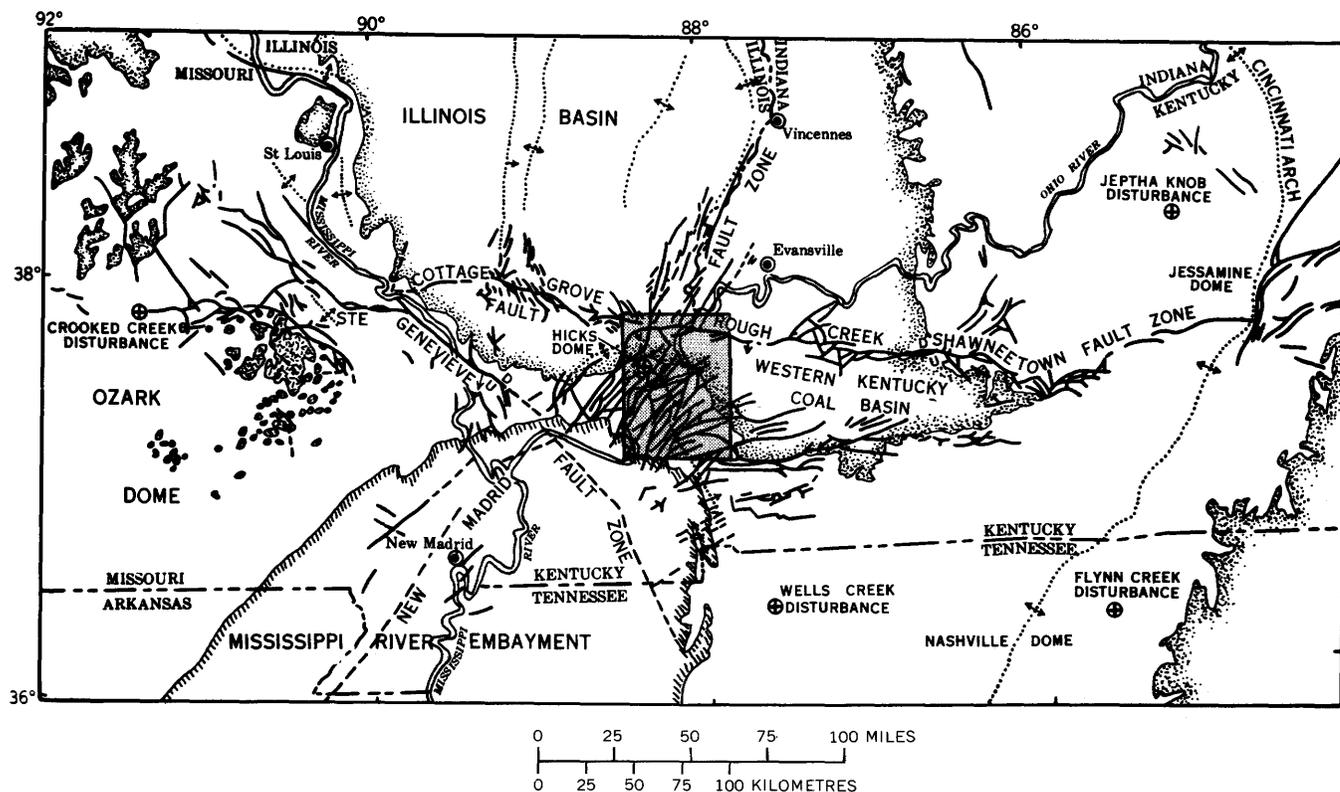
The Illinois-Kentucky mining district is centered in the most complexly faulted area in the central craton of the United States. Structural studies suggest that the mining district lies within a collapsed, block-faulted, sliced, and partly rotated domal anticline that is located at and near the intersections of several major fault lineaments.

(See fig. 26.) Prominent fault zones that intersect at the district are the east-trending Cottage Grove-Rough Creek-Shawneetown system—coinciding with Heyl's (1972) 38th-Parallel lineament—and the northeast-trending New Madrid fault zone.

Within the fluorspar district (fig. 23) the rocks are complexly broken by a series of steeply dipping to vertical normal or gravity faults that trend dominantly northeast and divide the area into a series of elongated northeast-trending blocks. Many cross-faults that trend north to northwest are occupied in places by mafic dikes. Near the east edge of the Kentucky part of the district, the faults trend more nearly east; and radial and arcuate faults are present around Hicks dome.

Hicks dome is a structural high with about 4,000 feet (1,200 m) of vertical uplift that is centered in the southwest part of the Karbers Ridge quadrangle (Baxter and Desborough, 1965). Brown, Emery, and Meyer (1954) described the dome as an incipient cryptovolcanic structure, on the basis of breccias (in an oil test hole and nearby at the surface), arcuate faults, and unusual mineralization. As a result of an aeromagnetic survey, McGinnis and Bradbury (1964, p. 11) stated that: "Hicks Dome is not underlain by a laccolithic intrusion. * * * A broad magnetic anomaly of relatively low intensity centered about 5½ miles [9 km] northeast of Hicks Dome and the featureless configuration of contour lines around the anomaly suggest a large igneous body overlain by a thick sedimentary rock section."

The southeasterly extension of Hicks dome is partly obscured by a fault zone 4-5 miles (6.5-8 km) wide known as the Rock Creek graben (fig. 23). Southeast of the graben, the structural high reappears as the Tolu dome or arch,



EXPLANATION

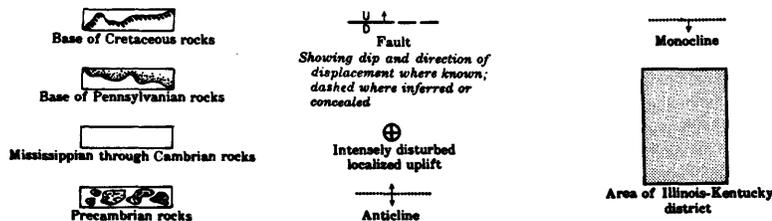


FIGURE 26.—Major structural features in the region surrounding the Illinois-Kentucky fluorspar district. Modified from Heyl and Brock (1961, fig. 294.1).

which is centered about a mile east of Tolu, Ky., in the Cave in Rock quadrangle (Baxter and others, 1963).

Southeast of the Tolu dome is another series of grabens (Weller and Sutton, 1951) bounded on the south by the Tabb fault system (Rogers and Hays, 1967); in this area a structural high is difficult to trace because of numerous faults. Possibly an extension of the high is shown on the Salem quadrangle (Trace, 1962a) between the Levias-Crittenden Springs fault system and the Moore Hill fault system. Farther south in the Dycusburg quadrangle, preliminary mapping suggests three more possible segments of the arch (Dewey Amos, oral commun., 1971) (see fig. 23).

Nearly all the faults of the district are normal and dip generally 75° to vertical; rarely are they inclined as low as 45°. Locally the dip of a fault or vein is reversed. Along the edges of many of the larger grabens, fault zones consist of several subparallel and sinuously intersecting faults. The total width of these zones may be more than 1,000 feet (300

m); more commonly it is a few hundred feet. Total displacement across the fault zone is commonly distributed irregularly among the several individual faults—in places as step faults and also small grabens within the fault zone, such that all faults either are vertical or dip toward the hanging wall of the fault zone. In some places, small grabens are formed by antithetic faults that dip toward the footwall side of the fault zone (fig. 27). Minor antithetic faults and fractures are present in places for a few hundred feet from the margins of the major graben.

Vertical displacement generally has been considered to have been the principal direction of movement along the major northeast-trending faults in the district. Clark and Royds (1948) and Heyl and Brock (1961), however, suggested that a horizontal component of movement may have been significant. Field mapping has shown that as much as 3,000 feet (900 m) of vertical displacement may have taken place, but movement generally has been much

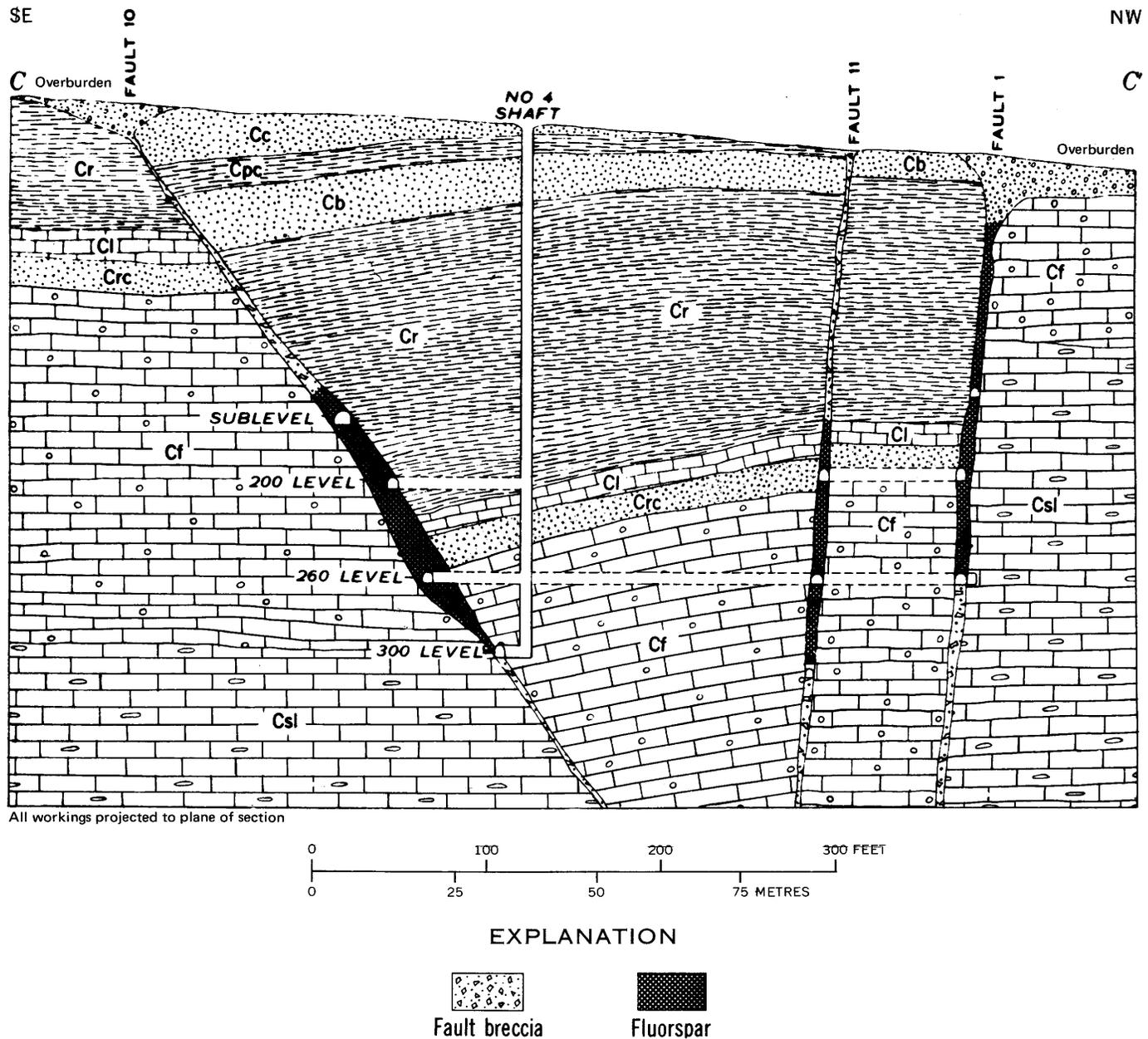


FIGURE 27.—Cross section of Davenport mine, Moore Hill area, Kentucky. Cc, Cypress Sandstone; Cpc, Paint Creek Formation; Cb, Bethel Sandstone; Cr, Renault Limestone; Cl, Levias Limestone Member of Ste. Genevieve Limestone; Crc, Rosiclare Sandstone Member of Ste. Genevieve Limestone; Cf, Fredonia Limestone Member of Ste. Genevieve Limestone; Csl, St. Louis Limestone. Modified from Thurston and Hardin (1954, pl. 14).

less. Evidence of strike-slip movement on the faults is conflicting; there is no evident horizontal offset of the northwest-trending mafic dike swarm where these elements are cut by northeast-trending faults, but there is some possible horizontal offset of the northwest-trending structural high (fig. 23) along these faults. Data from a few drill holes in the Crittenden Springs and Commodore areas (Salem quadrangle) suggest that the amount of vertical displacement on faults at depths of nearly 2,000 feet (600 m) below the surface is substantially the same as at the surface.

At least some and probably most of the major northeast-

trending faults are younger than Hicks dome and the mafic dikes, and therefore are post-Early Permian in age. The major displacement along these faults may have been completed by middle Cretaceous, although some movement has continued through Cretaceous and Tertiary time and up to the present (Rhoades and Mistler, 1941; Ross, 1963; McGinnis, 1963; Amos, 1967). Some faulting may have begun as early as Early Pennsylvanian time.

FLUORSPAR ORE DEPOSITS

Most of the fluorspar ore deposits are along northeast-trending faults; a few veins are found along the northwest-

and north-trending faults and in places are associated with mafic dikes (Trace, 1962b). The distribution of known deposits is shown on figure 23. D. R. Shawe observed (written commun., 1972) that the ore deposits tend to be concentrated in areas of mafic dikes and breccia pipes, as is suggested from figure 23; Trace is doubtful of the spatial association, however.

Fluorspar ore bodies occur dominantly either as steeply dipping to vertical vein deposits along faults or as low-dipping to nearly flat bedding-replacement deposits along certain stratigraphic horizons in Mississippian limestones (fig. 24; Currier and Wagner, 1944). A few deposits are a combination of vein and bedding-replacement type ores and so-called gravel deposits that resulted from a fluorite concentration in the residuum overlying vein deposits. Protore amounts of disseminated fluorite are present in the breccias of Hicks dome (Brown and others, 1954).

The fluorspar veins commonly are fissure fillings along faults and in fault breccias, accompanied by replacement of vein calcite and some wallrock. A typical vein is lenticular, pinching and swelling erratically, and is commonly a mixture of fluorite and highly variable quantities of calcite and country rock fragments. Locally the entire vein may be either calcite or fluorite. Commonly the vein walls are sharp but in places veinlets of fluorite and calcite extend into the slightly broken wallrocks for a few hundred feet.

The fluorite varies from commonly purple, fine- and medium-grained crystalline in small veinlets to commonly brown, white, or colorless, coarsely crystalline in more massive veins. In many places, the veins are complexly brecciated and (or) sheeted. Rude layering ("banding") parallel to vein walls is present locally. Shaly fault gouge, presumably dragged in along the fault from the more shaly of the Chesterian units, is common in places.

Most fissure-vein deposits average 3–10 feet (1–3 m) in width (Hardin and Trace, 1959; Trace, 1962b); a width of as much as 45 feet (14 m) is known. Mined ore shoots commonly range in strike length from 200 to 400 feet (60–120 m) though greater lengths are common in many places, particularly in the Rosiclare area. The average height of the ore shoots is 100–200 feet (30–60 m) but some ore shoots extend from the surface to a depth of nearly 800 feet (250 m) (Grogan and Bradbury, 1968, fig. 10).

The stratiform or bedding-replacement deposits are elongate bodies that trend northeast and less commonly southeast (fig. 28), and "are localized along a network of fractures and minor faults parallel to and half a mile distant from the Peters Creek fault ***" (Grogan and Bradbury, 1967, p. 41–42). In cross section, they appear as flat wedge-shaped or crescentic (concave upward) forms with thicker parts adjacent to individual faults: A few nearby pipelike breccia zones are mineralized and may have been

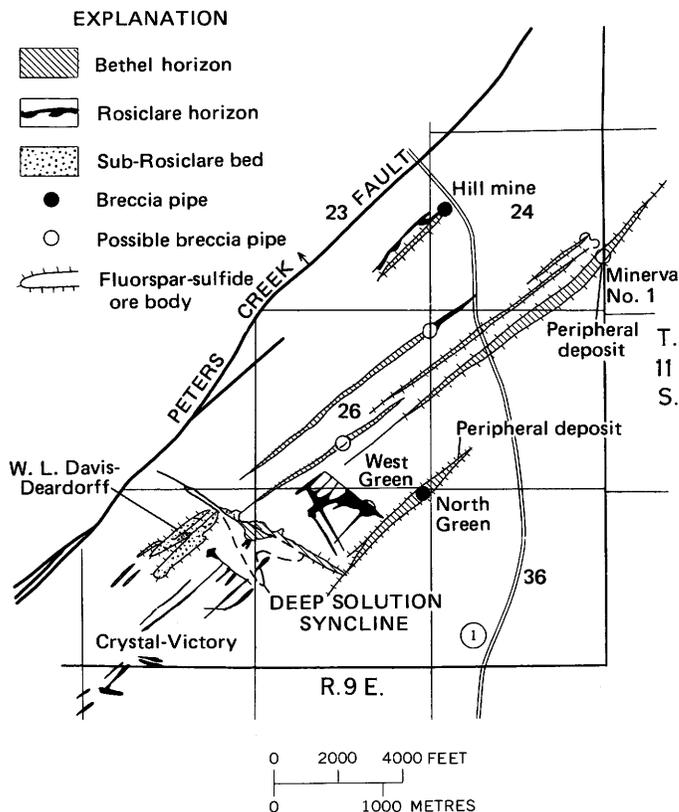


FIGURE 28.—Cave in Rock fluorspar district, Hardin County, Ill., showing elongate character of northeast-trending ore bodies. Modified from Brecke (1967, fig. 2, p. 381).

conduits for ore solutions (Brecke, 1962, p. 511–514; Grogan and Bradbury, 1968, p. 393–394).

The bedding-replacement ore bodies in Illinois are commonly 50–200 feet (15–60 m) wide, and 5–20 feet (1.5–6 m) thick; their length is highly variable, from 200 feet (60 m) to 2 miles (3 km). The grade of the ore also is highly variable, but the general grade of mine-run ore ranges from 20 to 35 percent of CaF_2 .

The bedding-replacement deposit being mined in Kentucky is believed to be approximately 2 miles (3 km) long, 150–250 feet (45–75 m) wide, and averages 7 feet (2.1 m) in thickness, containing about 30 percent of CaF_2 , and small quantities of zinc and barite (John S. Tibbs, oral commun., 1971).

Texture of the bedding-replacement deposits was described by Brecke (1962, p. 515–525) as "banded," imperfectly "banded," and brecciated. The latter two types characterize the majority of the deposits.

The deepest minable fluorspar in the Illinois-Kentucky district is in a vein in the Rosiclare area and at a depth of about 800 feet (235 m) (Grogan and Bradbury, 1968, p. 380). In the Kentucky part of the district the deepest mine working on a vein is about 700 feet (210 m). A substantial number of holes has been drilled in the Rosiclare area (Muir, 1947) to intersect the veins more than 1,300 feet (400 m) below the surface, but at that depth they are

dominantly calcite and wallrock breccia. In Kentucky a few holes have been drilled to almost 2,000 feet (600 m) below the surface, with virtually the same results.

The average grade of ore mined from the deposits has varied. Twenty to thirty years ago, the ore mined commonly contained at least 45 percent of CaF_2 , but gradually the ore cutoff grade has dropped, probably to somewhere between 25 and 40 percent of CaF_2 in 1972. Various factors have influenced the ore grade in addition to the selling price of the finished product, such as the amount of byproduct zinc and lead, and the varying costs of mining that depend primarily on the type of deposit and also on mine depth, amount of water, and degree of stability of mine walls or roof.

The most abundant minerals in the vein deposits are calcite and fluorite. Concentrations of sphalerite or barite are present in places, although more commonly sphalerite, barite, and galena occur in small quantities with the fluorite. Minor quantities of quartz, pyrite, marcasite, and chalcopryrite are present and locally zinc, lead, or copper alteration products (cerussite, pyromorphite, smithsonite, hemimorphite, greenockite, cuprite and malachite). Celestite has been reported in one locality in Kentucky (Hardin and Thurston, 1945).

The bedding-replacement deposits contain virtually the same suite of minerals. The principal difference is the quantity of calcite—abundant in the vein deposits, and common, though not abundant, in the bedding-replacement deposits. Fluorite is the principal mineral in the bedding-replacement deposits. Locally sphalerite, galena, and barite are abundant but generally they are uncommon. Calcite and quartz are widespread but sparse. Chalcopryrite, marcasite, pyrite, witherite, strontianite, smithsonite, cerussite, malachite, and pyromorphite have been reported.

Paragenesis of the vein and of the bedding-replacement deposits appears to be similar. Of the more abundant minerals, calcite is the earliest, overlapped and followed by fluorite. Sphalerite and galena generally appear to overlap and follow fluorite, and barite is the youngest common mineral. Hall and Friedman (1963, p. 891) reported on the paragenesis of the Cave in Rock deposits, and Pinckney and Rye (1972) reported on oxygen and carbon isotope variations in minerals deposited at different times in the wallrocks.

Fluid-inclusion studies of the temperature of deposition of the fluorspar have been done by Freas (1961) and Grogan and Shrode (1952). Their studies indicate a range in temperature from 90° to 140°C.

The composition of fluid inclusions in the ore and gangue minerals of the Cave in Rock area was studied by Hall and Friedman (1963). According to them, the general composition of the fluid inclusions suggests that the fluorite was deposited from a concentrated Na-Ca-Cl brine, probably of connate origin. Fluid inclusions in the quartz, however, have lower salt content, have a high ratio

of K/Na, Ca/Na, Cl/Na, and SO_4/Na , and a lower relative deuterium concentration than that found in the fluorite itself. These fluids may represent a magmatic water.

No apparent districtwide zoning of fluorite, sphalerite, and galena has been reported. Brecke (1964a) suggested that barite is more common on the fringes of the district, but exceptions in the Lola, Ky., area tend to obscure a broad picture of this zoning. Heyl (1969) suggested a zonation pattern for silver and antimony in galena, around Hicks Dome (see also Heyl and others, 1966), and a systematic change in the lead isotopic ratios from Hicks dome southeast into Kentucky.

Close dating of the age of mineral deposition has been difficult. Heyl and Brock (1961, p. D6) reported an age of 90–100 m.y. (middle Cretaceous) for monazite in fluorite-bearing breccia found at Hicks Dome, but this age is in doubt because of the weathered character of the monazite (Heyl, written commun., 1972). No other direct evidence exists for the age of the deposits.

Minor elements in the ore deposits have been reported by Hall and Heyl (1968). According to them, the fluorite is remarkably pure, except for the fluorite in breccias at Hicks dome which contains abundant rare earths. The sphalerite of the district is relatively high in cadmium, germanium, and gallium, but low in silver. The galena contains varying quantities of silver.

SUMMARY

The geologic history and genesis of the Illinois-Kentucky fluorspar district have been discussed by Amstutz and Park (1967), Brecke (1962, 1964b, 1967), Brown (1970), Grogan and Bradbury (1968), Hall and Friedman (1963), Hall and Heyl (1968), Heyl, Brock, Jolly, and Wells (1965), Heyl (1969), Oesterling (1952), Park and Amstutz (1968), and Snyder and Gerdemann (1965). The origin and chronological age of many of the significant geologic features of the district are still not established. Many structural and mineralogical events must have both overlapped and recurred, and therefore many a geologist has been confused and frustrated in attempting to establish the correct geologic history. In general, however, the history can be divided into three broad phases, all of which occurred principally within the interval of post-Middle Pennsylvanian to Cretaceous. The oldest events were the structural arching and formation of Hicks and Tolu domes, the intrusion of dikes and sills, and the formation of breccias. From the data of Zartman, Brock, Heyl, and Thomas (1967) these features appear to be early Permian in age. Next came most of the movement along the northeast-trending faults, followed by the third major phase, that of mineral deposition.

The general location of the Illinois-Kentucky district may be structurally controlled by the intersection of the northeast-trending faults of the New Madrid system with mafic dikes, and the structural high trending northwesterly through the district, and possibly with an east-

trending lineament of igneous activity described by Snyder and Gerdemann (1965) that is part of Heyl's (1972) 38th-Parallel lineament. In the district, the primary localizing elements, particularly for the vein deposits, were faults, which served both as ore solution channelways and as space for the ore bodies. Fractures and minor faults apparently were also a significant factor in the localization of the bedding-replacement deposits although the control exerted by these structures on the shape of the replacement deposits is somewhat less obvious than their control of shape of the vein deposits. In addition, relatively impermeable blanketing lithologic units, breccia pipes, and unconformities have been suggested as contributing to the localization of the bedding-replacement deposits. These factors were discussed by Brecke (1962) and by Grogan and Bradbury (1968).

The veins contain highly variable quantities of calcite and fluorite, and so far as the writer is aware, no guides are known to predict the calcite/fluorite ratio of a given vein, and thus to indicate the favorableness of the vein.

Vein widths appear to be directly related to the lithology of the fault walls (Grogan and Bradbury, 1968; Thurston and Hardin, 1954; Hardin, 1955; and Trace, 1962b, 1954). Most of the ore has been mined from veins where one wall and commonly both walls are made up of the Mississippian rocks from the St. Louis Limestone up through the Cypress Sandstone totaling about 1,000 feet (300 m) in stratigraphic thickness. Possibly this control was effective because these units are dominantly competent and massive in contrast to the post-Cypress units that contain many beds of incompetent shale, siltstone, and thin-bedded sandstone. Openings formed by faults where the walls are Cypress or older likely remained open for vein fillings, and incompetent shaly material was not as likely dragged into the fault zones. Also, in the more competent beds, the faults may steepen in dip, which could have allowed more space for mineral deposition. Similarly, where competent beds were faulted, the total displacement of the fault system was taken up by many faults (thus creating more space) rather than by a few faults with steeper drag-folded walls, such as where post-Cypress units were faulted.

Moderate fault displacement appears to have favored vein formation (Thurston and Hardin, 1954, p. 98); Grogan and Bradbury (1968, p. 390-392) suggested 25-500 feet (7.5-150 m) as the optimum displacement along faults occupied by veins.

A change in overall strike of a fault system may have influenced vein width in places. Possible examples are the Babb (Trace, 1962a) and Dyers Hill (Amos, 1967) areas in Kentucky and the Rosiclare area (Baxter and Desborough, 1965; Amos, 1966) in Illinois.

Several writers have noted the spatial association locally of vein deposits that are principally zinc-bearing (and also of fluor spar deposits that contain substantial byproduct zinc and lead) either along northwest-trending mafic dikes

(Hutson and Old Jim mines) or where dikes intersect northeast-trending faults (Hickory Cane mine). Recently a new deposit containing abundant sphalerite was found in Livingston County, Ky., near a mafic dike (The Mining Record, Denver, Colo., Dec. 23, 1970). On the other hand, the Nine Acres mine, Kentucky, contains principally sphalerite, but no mafic rocks are known in the immediate vicinity. As the dikes probably were intruded prior to mineral deposition, the genetic relationship between them and the mineralization is obscure.

Brecke (1967, p. 387) suggested that zinc sulfide deposition may have been related to iron sulfide present in the mafic rocks. Oesterling (1952, p. 332) suggested that sphalerite was deposited where post-fluorite faulting took place along the dikes. Hardin (1955, p. 23) stated that the distribution of sphalerite was controlled to some extent by the cross-faults and subparallel faults of the fault zone; that is, by implication, the sphalerite was related to late-stage faulting.

The deposits have been considered by most authors (Brown, Grogan and Bradbury, Heyl and associates) as epigenetic, with the ore elements mostly carried by hot connate water that was heated by deep-seated igneous activity, and carried upward along the faults to their present location. Some of the ore elements presumably were contributed to the connate water from deep-seated igneous activity.

One group (Amstutz and associates) suggested a syngenetic origin, and one writer (Brecke) suggested that connate water picked up the ore elements from the sediments and moved them laterally into the district from the southwest, without recourse to igneous activity.

Fluorspar reserves in the Illinois-Kentucky district are substantial. No comprehensive survey of reserves has been made since 1956 ("Fluorspar Reserves of the United States Estimated," press release, Office of Minerals Mobilization and U.S. Geol. Survey, November 23, 1956). However, a brief survey of the major producers in the district suggests that, under present economic conditions, new reserves found have at least been equal to production since 1956, and total reserves are probably adequate for at least 15-20 years.

New finds of near-surface gravel spar deposits probably will be rare, and there has been only slight to moderately encouraging results from deep exploration (deeper than 1,000 feet-300m). Large numbers of faults within the district have not been adequately tested at intermediate depths or even shallow depths in places, suggesting that the district has much additional potential and will be a source of fluorspar for many years. Currently, exploration is increasing, and several new discoveries have been made in the last several years.

Large quantities of low-grade fluorite in the breccias at Hicks Dome are too lean to be mined now; under more favorable economic conditions and with possible byproduct production, large-scale mining operations on

the breccias might be undertaken in the future. Mining of the breccia ores at Hicks dome could increase substantially the resources of the Illinois-Kentucky fluorspar district.

CENTRAL KENTUCKY

The Central Kentucky district, covering more than 2,000 mi² (5,000 km²) in Boyle, Clark, Fayette, Garrard, Jessamine, Lincoln, Madison, Mercer, and Woodford Counties, has yielded about 30,000 tons of fluorspar over a period of many years; the largest production was made in 1947 (Sutton, 1953, p. 140), and the district in 1972 is inactive. Veins cut Middle Ordovician limestones along strike-slip and normal faults (Currier, 1923; Robinson, 1931; Earl, 1959; Jolly and Heyl, 1964). The veins are localized along the Kentucky River fault zone astride the Lexington dome and the Cincinnati arch. Most of the nearly vertical veins trend approximately northerly and range in width from less than an inch (2.5 cm) to about 6 feet (2 m). A few veins trend easterly or northeasterly. They have been mined to a depth of 220 feet (67 m). Lateral zoning in this district (Jolly and Heyl, 1964) consists of an inner two zones with fluorite and an outer zone of barite-galena-sphalerite. Textures range from coarse comb crystals in the inner zone to fine colloform layers in the outer zone. Fluorite, sphalerite, galena, barite, strontian barite, and calcite are major minerals. Celestite, strontianite, marcasite, pyrite, chalcopyrite, quartz, witherite, and ferroan dolomite are minor minerals. The vein walls are almost unaltered. The veins are epithermal fissure fillings and breccia replacements that formed in late Paleozoic time.

Exploration in progress in 1972 in the Central Kentucky district was searching for sulfide-bearing breccia deposits similar to those in the Lower Ordovician carbonate strata of the Cumberland River vein district and the Central Tennessee district. The carbonate rock stratigraphy changes westward in central Kentucky across the Cincinnati arch and so lithologies are more like those in central Tennessee, making the probabilities of deposits similar to those in central Tennessee better on the eastern side of the arch. Widespread faults in the Central Kentucky district probably provided channels for easy flow of ore-bearing solutions and allowed formation of fissure veins. Bedded and breccia deposits more probably occur in areas sparsely faulted and still capped by unbroken semi-permeable shaly beds. Such geologic conditions exist southward along the Cincinnati arch toward Tennessee and to a lesser extent northwestward toward Louisville, Ky. Probabilities are good for the development of new commercial deposits of fluorspar on the known veins, and for discovery of new fluorspar veins in the central part of the district.

CUMBERLAND RIVER, KENTUCKY

A northward extension of the Central Tennessee district, described below, lies along the Cumberland River in Monroe, Cumberland, and Russell Counties, Ky. (Jolly

and Heyl, 1968), where small veins containing traces of purple fluorite, but otherwise mineralogically identical with those in central Tennessee, have been prospected. These veins in Middle Ordovician limestones lie 30–50 miles (50–80 km) northeast of the main Central Tennessee district in an area of good outcrops. Unquestionably they indicate an extension northeastward of the district, and a possible connection of the Central Tennessee district with the Central Kentucky district along the crest of the Cincinnati arch. Breccia fluorspar deposits similar to those in the Central Tennessee district may occur in quantity in the Lower Ordovician and lower parts of the Middle Ordovician carbonate strata in this Cumberland River vein district.

TENNESSEE-NORTH CAROLINA-VIRGINIA

CENTRAL TENNESSEE

The Central Tennessee zinc-fluorspar-barite-lead district (Jewell, 1947; Maher, 1970) covers about 2,400 mi² (6,200 km²) in Smith, DeKalb, Putnam, Trousdale, Wilson, Davidson, Williamson, Rutherford, and Cannon Counties, and was the source of about 1,500 tons of hand-picked fluorspar in 1902–06, 1914–18, 1925–28, 1935–36, 1942–43, and 1956. This district is on the Nashville dome, which is structurally connected by the Cincinnati arch to the similarly mineralized Lexington dome farther northeast.

After the Illinois-Kentucky fluorspar district, the Central Tennessee district may have the largest fluorspar resource potential in the United States, occurring in still-unmined breccia blankets of fluorspar, barite, sphalerite, and calcite in Lower and Middle Ordovician carbonate rocks. Past production of fluorspar nevertheless was entirely from nearly vertical veins cutting Lower Ordovician to Mississippian rocks; most deposits are in limestone of Middle Ordovician age. Igneous rocks are lacking in the district. The veins formed largely by fissure filling and replacement of breccia fragments; there is little evidence for replacement of the limestone walls. Mineralized faults, commonly having horizontal displacement, generally trend northeast; most northwest-trending faults are post-ore. Most veins are less than 3 feet (1 m) thick but veins range in thickness from a few inches to 6 feet (2 m) where the vein material consists of well-layered material, and to 15 feet (4.5 m) where the vein is a mineralized breccia zone.

A few small bedded replacement bodies or pipes of fluorite have been mined or prospected here in the Middle Ordovician limestone. Nearly all the known deposits exposed at the surface were described by Jewell (1947). The vertical extent of some deposits is at least 200 feet (60 m). A few veins may extend for 1,000 feet (300 m) in length. The veins consist chiefly of strontian barite, multicolored fluorite, sphalerite, galena, calcite, quartz, dolomite, and a little chalcopyrite and pyrite and their oxidation products. A few veins consist almost entirely of sphalerite and

calcite. Analyses of vein material (Jewell, 1947, p. 21) show the following ranges: 3-86 percent CaF_2 , 1-79 percent BaSO_4 , 3-60 percent CaCO_3 , less than 1-3 percent SiO_2 . As on the Lexington dome, fluorite is the prominent mineral near the center of the Nashville dome, and the mineral zoning and paragenesis in these two districts are quite similar (Jolly and Heyl, 1964, p. 618). Some veins were worked also for lead, zinc, or barite, and possibly some of them may yield coproducts in the future. Most veins, however, are much too small to be important future producers. According to Jewell, the veins have never been adequately explored. They are regarded as low-temperature hydrothermal deposits (Jolly and Heyl, 1964, p. 621; Jewell, 1947, p. 37) formed from heated saline brines in post-Carboniferous time.

Large blanket and podlike breccia deposits of fluorspar, barite, sphalerite, and calcite have been found at depth in recent years in the Central Tennessee district during extensive exploration programs by many companies searching for zinc deposits similar to the large ones discovered by the New Jersey Zinc Company near Carthage, Tenn. In contrast to the overlying veins the deeper deposits are lead-free or lead-lean. In these deposits dolomite is sparse and replacement features uncommon, unlike the somewhat similar deposits in eastern Tennessee near Sweetwater. Fluorite, most of it colorless, cements breccia fragments of limestone, dolomite, and gray jasperoid. Several ages of breccia are known, but most of the mineralized breccia bodies are in the middle and upper parts of the Lower Ordovician Kingsport Dolomite. Some bodies extend through the unconformity at the top of the Lower Ordovician rocks up into overlying Middle Ordovician limestones. Fluorite-bearing aureoles of potential byproduct value may exist around some of the zinc-rich ore bodies as well as around the fluorite breccia bodies. Large parts of the Central Tennessee district that are marked by small veins are still scarcely prospected; notable are the southern and southwestern parts along the crest of the Cincinnati arch.

SWEETWATER, TENNESSEE

According to Brobst (1958, p. 102), the Sweetwater district in parts of McMinn, Monroe, and Loudon Counties has yielded most of the barite mined in Tennessee. The barite occurs with fluorite, sphalerite, and pyrite in veins or shatter zones in the upper part of the Knox Group of Cambrian and Ordovician age and it is concentrated in the overlying residual clays. Only the residual barite deposits have been mined. Fluorite is generally absent in the residual deposits and no gravel spar is known, a fact that has largely obscured the true composition of the deposits.

In bedrock the deposits contain almost as much fluorite as barite, and in places considerable sphalerite (Laurence, 1939, 1960). D. A. Brobst (oral commun., 1972) confirms this widespread abundance of fluorite throughout the district wherever the unweathered primary deposits are exposed. Many of the bodies in the shattered zones are large, and except for the main minerals in them are geologically similar to the collapse breccia and

disseminated zinc ore bodies of eastern Tennessee. In the main zinc deposits of Tennessee, barite and fluorite are sparse late minerals, but elsewhere in the zinc districts of the Appalachian Valley and Ridge province between Alabama and Pennsylvania all gradations of deposits occur from nearly pure sphalerite to barite (or barite-fluorite).

Deposits in the large Sweetwater district occur in three parallel northeast-trending belts of limestone and dolomite separated by zones devoid of deposits. According to Brobst (1958, p. 102) the three belts of gently east-dipping Knox Group strata lie in nearly parallel fault blocks bounded by southeast-dipping thrust faults. Workable bodies of residual barite ore occur at irregular intervals along the three belts. Unlike fluorspar in the Central Tennessee district to the west, the fluorspar here was apparently dissolved during weathering and did not accumulate in the residual clays as did the barite (D. A. Brobst, oral commun., 1972). Thus the absence of fluorspar in the residual barite deposits does not indicate either its absence or its possible abundance in the bedrock deposits. In fact a possibility for exploration would be to test the bedrock beneath the leaner barite residual deposits to determine whether sparsity of barite indicates more abundant fluorite.

The eastern belt is 20 miles (30 km) long and the other two belts are each 40 miles (65 km) long. Individual commercial deposits of barite extend over many acres, and zinc deposits are known in the district. The marked geologic similarity (including the same favorable strata) between the primary unweathered deposits and the huge zinc deposits of eastern Tennessee farther north suggests that a major fluorspar-barite (and in places zinc) resource potential exists here; it may be one of the larger deposits in the country. Careful exploration and evaluation of the primary deposits are required to determine whether they are economic in grade and adaptable to known milling techniques.

DEL RIO, TENNESSEE-HOT SPRINGS, NORTH CAROLINA

The Del Rio district in Cocke County of easternmost Tennessee and the Hot Springs district in Madison County of westernmost North Carolina are two parts of one mineralized area of barite and fluorite (Stuckey, 1942; Oriel, 1950; Ferguson and Jewell, 1951; Brobst, 1958). A moderate tonnage of barite has been produced from both districts and a small tonnage of fluorspar from the Del Rio district (Ferguson and Jewell, 1951). The mineralized area forms a belt that trends east for about 20 miles (30 km) across the crest of the Blue Ridge Mountains. The belt is about 10 miles (15 km) wide at its widest, which is in the Del Rio district. Many mines and prospects are in the 100-mi² (260 km²) area. Most of the mining has been in residual deposits in deeply weathered zones.

The rocks in the Del Rio district are gneiss, schist, and quartzite of the Snowbird Group, and the Sandsuck

Formation, all of Precambrian age (Brobst, 1958, p. 90), and clastic rocks of the Unicoi and Hampton Formations of Early Cambrian(?) age, the Erwin Formation of Early Cambrian and Early Cambrian(?) age, and the Shady Dolomite and shale of the Rome Formation of Early Cambrian age (Ferguson and Jewell, 1951, p. 12). These rocks occur in two overthrust sheets that have been thrust from the southeast.

Minerals in the deposits are barite, fluorite, ankerite, dolomite, sericite, specular hematite, quartz (including jasperoid), pyrite, and copper minerals; in some places all these minerals are present, in others, only a few. Fluorite is found in most deposits, and in places exceeds 20 percent of the total. The ore bodies were probably deposited at higher temperatures than those that prevailed at Sweetwater, Tenn.

Most of the primary deposits in the Hot Springs district in North Carolina are fissure veins in quartzite. In the Del Rio district, the primary deposits are of two other types: (1) replacement of finely granulated sheared gouge and breccia in thrust faults, and (2) cementation and replacement within tension fracture zones and along bedding planes and permeable beds. Some of the ore bodies of the second type are large and constitute an important resource of many tens of thousands of tons of barite and as much as 20 percent fluorite that could be recovered by concentration mills.

HAMME, NORTH CAROLINA-VIRGINIA

The Hamme tungsten district is in the Piedmont province, almost centered along the North Carolina-Virginia State line between Vance County, N. Car., and Mecklenburg County, Va. High-temperature fissure veins occur near the granite-schist contact, mostly in granite (Espenshade, 1947; Parker, 1963).

Tungsten-bearing veins lie in a northeast-trending belt about 8 miles (13 km) long. Individual veins range in length from a few feet to at least 1,000 feet (300 m) and they extend to depths exceeding 1,000 feet (300 m). The principal minerals are quartz, huebnerite, scheelite, fluorite, garnet, apatite, sericite, rhodochrosite, topaz, pyrite, argentian galena, calcite, tetrahedrite, sphalerite, and chalcopryite; a little gold is present. Fluorite is the most abundant mineral aside from quartz, but it has not been recovered as a byproduct even though it occurs in nearly every tungsten-bearing quartz vein. The fluorite is pale green, blue, and purple where fresh, but bleaches to white upon exposure to sunlight.

Espenshade (1947, p. 7) reported that about 4 percent of fluorite was noted in the mill tailings in the early years of the Hamme mine. The deposits are large, and for about 20 years the Hamme mine was the largest tungsten mine in the United States. A substantial fluorspar resource is present in this district and fluorite could be recovered from the mill tailings and as a byproduct of mining when the mine is reopened.

FABER, VIRGINIA

A long vein of quartz, fluorite, argentian galena, sphalerite, and chalcopryite produced some zinc, lead, and a small quantity of fluorite during 1905-19 in Albermarle County, 2 miles (3 km) east of Faber (Luttrell, 1966, p. 46-47). The fissure vein trends northeast and lies in the western part of the Piedmont province in a heavily wooded area where outcrops are scarce. The vein occurs in a shear zone within biotite-chlorite-muscovite gneiss. Little effort, as far as is known, has been made to determine if other veins occur in the vicinity.

OTHER DEPOSITS, VIRGINIA

Appalachian-type deposits of barite, sphalerite, and fluorite are common in three parts of Virginia: (1) the Gate City-Lebanon area in southwestern Virginia, (2) the Marion-Austinville area in south-central Virginia, and (3) the northern part of the Shenandoah Valley of Virginia, where there are little-known fluorite veins and zinc-fluorite breccias near Woodstock and Lebanon Church at the northeastern end of the Timberville zinc district.

The Gate City-Lebanon area includes a long discontinuous line of deposits of sphalerite, barite, and fluorite that trends east-northeast for at least 50 miles (80 km) through Scott, Russell, Tazewell, and Bland Counties. Fluorite, locally forming as much as 20 percent of a deposit, occurs with the sphalerite and barite in mineralized breccia zones in Kingsport Dolomite of Early Ordovician age similar to those at Sweetwater, Tenn. Residual barite deposits occur in places and the entire belt needs re-examination in terms of a possible fluorspar potential similar to that in the Sweetwater district, Tennessee.

An area of similar deposits extends at intervals from Marion, Virginia, to the Austinville-Ivanhoe zinc-lead district farther east. Some of the western deposits near Marion contain abundant fluorite. They consist of barite-fluorite-sphalerite breccia bodies. West of Marion, for example, is the Myers deposit of coarse platy white barite, colorless and purple fluorite, pale-yellow sphalerite, and a little pyrite, in the upper part of the Kingsport Dolomite. Fine-grained gray dolomite and black and gray jasperoid are the main gangue minerals. The mineralized zone is in a vertical body of collapse breccia aligned along the crest of an anticlinal nose.

In the eastern parts of this area south of Austinville and Ivanhoe similar barite-fluorite deposits are known, but little prospected, in the Shady Dolomite and in the Unicoi Formation, of Cambrian and Cambrian(?) age respectively; deposits in Grayson County are in Precambrian gneiss, schist, granite, and volcanic rock. At the Poole barite prospect on the east bank of the New River 5 miles (8 km) east-northeast of Independence, a fissure vein as much as 16 inches (40 cm) wide of fine-grained barite, epidote, chlorite, fluorite, and quartz has been prospected by three shallow shafts (Edmundson, 1938, p. 48-49).

Another locality is the Simmerman prospects, 5 miles (8 km) east of Ivanhoe Ferry, in the Cambrian Shady Dolomite. There, in old pits, where the iron ore is undoubtedly a limonite gossan, brecciated dolomite outcrops contain sphalerite, galena, fluorite, barite, cherty quartz, and calcite (Luttrell, 1966, p. 119).

Fluorite occurs in small quantities throughout the Timberville zinc district of northern Virginia in Augusta, Rockingham, and Shenandoah Counties. The mineral is abundant at the Tusing prospect 4.9 miles (7.9 km) S. 82° W. of Mount Jackson (Herbert and Young, 1956, p. 36). Here coarse purple fluorite occurs in disseminations associated with yellow sphalerite and calcite throughout a bed of crystalline dolomite. Between 1956 and 1965 a prospect shaft was dug on the property, and a bin was filled with a few tens of tons of sorted fluorite-sphalerite ore (C. H. Maxwell, 1972, oral commun.). Maxwell estimated that the sorted coarse-grained ore contained about 50 percent purple, colorless, and pale-yellow fluorite, 30 percent honey-yellow sphalerite, and the rest barite and calcite.

About 8 miles (13 km) northeast of the Tusing prospect is the most probable location of the Barton fluor spar vein, which is reported to be many feet wide and to trend northerly (Silliman, 1821, p. 243-244). This vein, which was described and then forgotten in the early 19th century, is reported to be in limestone at the very foot of the southeast slope of Little North Mountain, northwest of Woodstock. The vein is reported to consist of purple fluorite and calcite. It is on a small ridge and between two walls of limestone. At the time of the discovery of the vein prior to 1820, fluor spar had little or no value and the exact location of this vein is now lost.

About 10 miles (15 km) northeast of the Barton vein, and 0.5 mile (0.8 km) northwest of the village of Lebanon Church in northernmost Shenandoah County, a similar deposit of fluor spar was found in the 1960's by C. H. Maxwell (oral commun., 1972). It lies at the southeast foot of Little North Mountain on a small knoll of Paleozoic limestone. Coarse pieces of residual colorless and yellow fluorite are abundant in the yellow clay soil atop the knoll between two low outcrops of northeast-trending limestone.

The above three deposits of fluor spar found at intervals along a 20-mile (30-km) trend at the foot of Little North Mountain may indicate a fluor spar district of commercial importance. Similarly occurring and equally little-known occurrences of sphalerite near Timberville, farther south, led to the exploration and development of the Timberville zinc district in the early 1950's.

ALABAMA

Deposits notably similar to those in the Sweetwater district, Tennessee, are known in slightly older carbonate rocks in Alabama at the Sinks district, Bibb County and at

the Gilley (or Gilly) deposit in northeastern Alabama in Calhoun and Cherokee Counties. The Gilley deposit has produced a small quantity of fluor spar from veins and other concentrations in Conasauga Limestone of Cambrian age (O'Neill, 1950). This deposit and several other residual barite deposits and fluor spar occurrences in Alabama and in nearby Georgia (Brobst, 1958, p. 106; Worl and others, 1974) need reevaluation in respect to possible similarities to the Sweetwater, Tenn., deposits.

MISSOURI-ARKANSAS-CENTRAL TEXAS

SOUTHEAST MISSOURI

The Precambrian magnetite deposits being mined in 1972 at Pilot Knob and Pea Ridge, Mo., and the recently closed mine at Iron Mountain, all contain fluorite and fluorapatite. Both fluorine minerals are locally abundant in these large deposits. For example, the initial new shaft put down in recent years at Pilot Knob cut a fluorite-chalcocopyrite-magnetite body of sizable tonnage (P. W. Guild, oral commun., 1967). Elsewhere in the district the abundance of purple and colorless fluorite and associated apatite is apparent and in parts of the Pilot Knob ore body the mineral may constitute as much as a few percent of the ore.

The same potential for byproduct fluorite and copper concentrates exists here as in the Adirondack Mountains. The partly developed Boss iron-copper deposit, as well as the Bourbon and Sullivan magnetite deposits, should also be examined for fluorite potential.

OTHER DEPOSITS, MISSOURI AND ARKANSAS

Fluorite occurs elsewhere in the Precambrian of southeast Missouri. Fluorite is found with calcite and apatite in a veinlet in a granite quarry at Granite, north of Ironton; disseminated fluorite is reported in this same granite. Fluorite occurs in high-temperature Precambrian veins with quartz, topaz, cassiterite, wolframite, and silver-rich galena at the Einstein silver-tin mines southwest of Fredricktown.

Coarse yellow fluorite and pink platy barite occur in large gas cavities in a Devonian kimberlite breccia on the O.K. Cash farm southeast of Avon, Mo. (Zartman and others, 1967). The kimberlite, which contains many limestone fragments, is fluorine rich. Fluorite is abundant enough to suggest that the 70 or so other Devonian intrusives near Avon should be examined for fluorite.

Fluorite is locally abundant in the Magnet Cove and Fourche Mountain, Arkansas, alkalic igneous rock complex, and in small veins in the southern Ouachita Mountains, Arkansas. A search might be warranted on the margins of these complexes and near the contacts of the other alkalic syenites in central Arkansas for fluorite deposits of commercial size, especially where the wallrocks are limestone or dolomite.

LLANO UPLIFT, CENTRAL TEXAS

Fluorite deposits and occurrences are common in Pre-

cambrian granites and gneisses in the Llano uplift west of Austin (Paige, 1911), particularly northwest of Austin at Burnet where a small quantity of fluorspar was produced in 1943. The deposits are mostly disseminations of fluorite and clusters of small fluorite veins in granite and in gneiss. The main deposits form a small cluster 4–7 miles (6.5–11 km) west of Burnet along the north fork of Spring Creek. Fluorite and topaz are also common in the complex pegmatites of the Llano uplift such as those on Barringer Hill. Fluorite is disseminated in the granite of Opaline in Llano County and in the Oatman Creek Granite of Stenzel (1932) along Honey Creek in Mason County. The Llano uplift appears to be a favorable area in which to search for commercial fluorite deposits.

A topaz placer occurs in the Llano uplift of central Texas (Paige, 1911). The bedrock source of the coarse-grained white topaz has not been found, but it is probably in pegmatite. The deposit, which has been prospected but not mined, is near Streeter in Mason County. The occurrence of topaz in pegmatites and granites elsewhere in the uplift suggests that other such topaz placers may exist.

NEW YORK

ADIRONDACK MOUNTAINS

Nearly all the Precambrian magnetite deposits of the Adirondack Mountains of New York contain fluorite, but in most deposits fluorite is a sparse mineral. Certain types of skarn magnetite deposits, however, contain locally abundant fluorite; in places the mineral forms 5–60 percent of the deposit. Types of skarns that may contain locally abundant fluorite (according to Leonard and Buddington, 1964, p. 33–35) are clinoamphibole skarn, biotite skarn called “sköl,” (in which the mica is in contorted streaks, masses, and selvages), and a modified scapolitic skarn, which is derived by further metamorphism from the other types. All types except the scapolitic fluorite-bearing skarn are associated with magnetite deposits. Some of the larger fluorite-bearing deposits are the Parish, Trembley Mountain, and Jayville, all in the St. Lawrence magnetite district, the Palmer Hill iron deposits in the northeastern Adirondack Mountains, and the Mineville deposits in the southeastern Adirondack Mountains.

Many of these skarn magnetite deposits are large. They range in length from 800 to 4,000 feet (250–1,200 m); generally they are 1,000–2,000 feet (300–600 m) long and 30–65 feet (10–20 m) wide and extend to depths greater than 500 feet (150 m) (Leonard and Buddington, 1964, p. 39–40). Deposits of this size may contain up to several million tons of iron ore. Many deposits are much smaller.

An example of a skarn magnetite deposit that is rich in fluorite is the Jayville deposit, 1.25 miles (2 km) east of Kalurah, St. Lawrence County, in the western Adirondack Mountains. The mine has yielded several tens of thousands of tons of magnetite ore; associated with the

magnetite ore are supergene hematite, vonsenite (ferrous-ferric borate), fluorite in dark mica skarn (sköl), pyroxene-amphibole skarn, and quartz-bearing amphibole skarn. Parts of the amphibole skarn and the iron ore are rich in fluorite; this type of skarn is as much as a few feet thick and ranges from 20 to 60 percent fluorite (Leonard and Buddington, 1964, p. 134, 142). If the iron deposit is mined again, fluorite and vonsenite (borate) should be considered as coproducts.

The Parish fluorite-bearing iron deposit is about 6 miles (10 km) east of Degrasse in the central part of St. Lawrence County. The deposit is probably 4,000–5,000 feet (1,200–1,500 m) long, has an average thickness of 55 feet (17 m), and has been explored by drilling to depths of 600 feet (180 m). The deposit consists of magnetite-hematite ore with spessartite garnet, chalcopyrite, bornite, pyrite, and fluorite. In places the fluorite constitutes several percent of the ore (Leonard and Buddington, 1964, p. 223). Potentially the deposit has several valuable coproducts including the fluorite. If methods now applied elsewhere to recover the magnetite and hematite were used, and in addition copper sulfide and fluorite concentrates were recovered, this large deposit would have more value than deposits from which iron alone is recovered.

At Mineville, rare-earth fluorapatite, rare-earth fluorocarbonates (including bastnaesite), and fluorite occur in several deposits (McKeown and Klemic, 1956). Large quantities of these minerals are already partly concentrated in the mill tailings, making a potential ready source of fluorine and thorium- and yttrium-bearing rare earths.

North of Mineville, at Palmer Hill, fluorite and fluorapatite are abundant in the iron deposits, and in one mine an undeveloped vein of fluorite is reported adjacent to the magnetite ore.

The magnetite deposits of the Adirondack Mountains should be considered a major potential source of fluorine, mostly as a coproduct or byproduct of iron mining. To date the fluorite has not been recovered. The potential tonnage of fluorite in the magnetite deposits is very large, probably exceeding a million tons.

OTHER DEPOSITS

Fluorspar has been produced from only two of several fissure veins in the Rossie vein district of northern New York. The production has not been large, and the vein system only locally contains commercial concentrations of green and colorless fluorite. More commonly, galena and sphalerite are the main ore minerals. The veins, which are large and wide, are in vertical faults, mostly of north-westerly trend on the south flank of the Frontenac arch. The faults have large strike-slip components, and are post-Precambrian in age. The deposits are low temperature and contain coarse-grained minerals. Galena in the veins is radiogenic. In these respects and in all others, the veins can be classified as Mississippi Valley-type. The veins in the district are not well known and have not been prospected

extensively; a belt may extend northwestward from Lowville well into southern Ontario to the Madoc fluorspar district. The Rossie district, though of secondary resource potential, should be reevaluated in terms of its fluorspar possibilities.

NEW ENGLAND

CHESHIRE COUNTY-WESTMORELAND, NEW HAMPSHIRE

The most productive fluorspar district in New England is about 2.5 miles (4 km) southwest of Westmoreland, Cheshire County, where about 8,000 tons (7,262 t) was produced in 1911-23 and 1935-38 (Bannerman, 1941). The deposits are 2-3 miles (3-5 km) southeast of the Connecticut River valley in granite gneiss overlain by hornblende schist, quartzite, and staurolite-mica schist. Lenticular fluorite-quartz veins are found near the contact with overlying hornblende schist. Blue-green fluorite occurs in lenses, pockets, and fine-grained intergrowths with quartz, calcite, and barite; streaks of sulfide minerals are rare. The sulfide minerals are chalcopyrite, galena, pyrite, sphalerite, and bornite. The small production came from shallow workings on seven veins. An ore sample from a dump contains 35 percent CaF_2 and 60 percent SiO_2 (Bardill, 1946, p. 5). A vein intersected by a drill hole 150 feet (45 m) deep contained only about 2 percent fluorine and less than 1 percent barium.

These deposits and others in New Hampshire may be related genetically to Devonian granites, as Cox (1970, p. D3-D4) suggested for fluorite-bearing deposits associated with the Conway Granite. Possibly, however, the structural position of the Cheshire County-Westmoreland district in the Connecticut Valley graben, on trend with mineralogically similar Triassic or younger veins in Massachusetts, indicates a Triassic or younger age for the veins in southern New Hampshire. The small veins of fluorite nearby at Putney, Vt., are probably genetically related.

The Cheshire County-Westmoreland veins were productive even without milling; the fluorspar was concentrated by hand sorting. Thus only the coarsest and purest ore could be shipped. Bannerman's (1941) description of the veins indicates that only the richest parts of the known veins were mined, and only to shallow depths. Some lower grade veins amenable to milling were not mined, and he considered indications good that the veins extended to greater depth. Thus the district may have a future as a potential resource of moderate size.

NORTH CHATHAM, NEW HAMPSHIRE

Granite pegmatites near the village of North Chatham contain fluorite and topaz along with beryl, lepidolite, and muscovite. Locally, the fluorite is so abundant that a few tons was mined many years ago (Morrill, 1951). The pegmatites are possibly related to the Conway Granite of the White Mountain Series. Many nearby pegmatites in western Maine contain fluorite and topaz.

LONG HILL (TRUMBULL)-MONROE, CONNECTICUT

One of the first producers of fluorspar and tungsten in the United States is north of Bridgeport in southwestern Connecticut. In 1837 fluorspar was mined from a vein on the southern crest of Long Hill in the Township of Trumbull and used as a flux to smelt copper ores (Hatmaker and Davis, 1938, p. 17). Coarse-grained green, colorless, and pale-purple fluorite occurs in a few large east-trending fissure veins of fluorite, topaz, quartz, margarite, margarodite, wolframite, scheelite, and arsenopyrite. Pegmatites a few hundred feet north of the veins contain coarse fluorite in miarolitic cavities, and fluorite is reported also to occur with scheelite in marble and in a skarn contact zone between the Straits Schist and the Collinsville Formation of Crowley (1968). Fluorite occurs north of Long Hill in smaller quantities at Lanes mine, 1 mile (1.6 km) west of Monroe village. There it is in a quartz vein with sparse tungsten and silver-lead, bismuth, and arsenic minerals. A few miles southeast of these deposits is the Pinewood Adamellite of a quartz monzonite (or adamellite) stock, which contains disseminated fluorite (Crowley, 1968). Intrusives of this type at depth may have been the source of the fluorite on Long Hill. Although this area is favorable for other fluorspar deposits, and fluorite is still available in the known veins, Long Hill is now a State Park, and both it and Lanes mine are being engulfed by the suburban area of southern Connecticut.

LONG ISLAND, BLUE HILL BAY, MAINE

A hundred-foot-wide tactite zone of eastward trend more than a mile (1.5 km) long crosses the northern third of Long Island, southeast of Blue Hill, Maine. The zone is part of the northern tactite-bearing contact between biotite granite and Ellsworth Schist. The tactite contains appreciable scheelite, molybdenite, apatite, a beryllium mineral, and coarse crystals of green fluorite. A very small quantity of the fluorite was mined in 1838 and sold to apothecary shops (Hatmaker and Davis, 1938, p. 17). The contact zone potentially may be an important resource of the coproducts fluorspar, tungsten, molybdenum, and beryllium.

OTHER DISTRICTS AND DEPOSITS OF THE CENTRAL AND EASTERN UNITED STATES

Parts of the Midwest region, other than those already described, that should be examined for possible new fluorspar districts are: (1) northern Ohio in the vicinity of Toledo where fluorite is known in limestone quarries on a structural dome; fluid-inclusion studies by Edwin Roedder (oral commun., 1970) indicate that the fluorite was deposited by hot concentrated brines and therefore may be present in substantial deposits; (2) Serpent Mound cryptoexplosion structure in Adams and Highland Counties, southeastern Ohio, where some fluorite and barite cement the breccias in places; (3) southern Indiana, west of Louisville, Ky., where a few minor fluorite

occurrences are known in limestone quarries—possibly indicative of an undiscovered district; (4) many minor occurrences of fluorite, barite, sphalerite, and galena in and near the Ste. Genevieve fault zone of southeast Missouri and southern Illinois, which also may be an undiscovered Illinois-Kentucky-type fluorspar and sulfide district.

Fluorite is a common mineral in many of the other southwestern Virginia barite and zinc deposits, including a cluster in the vicinity of Roanoke. Indeed, Edmundson (1938, p. 12) stated that "fluorite was identified in all of the barite areas [in Virginia], being particularly abundant in the deposits of the Appalachian Valley and Ridge province." Thus a reexamination of all the barite deposits (and some of the zinc deposits) in terms of fluorspar potential in the Valley and Ridge province may be warranted. Similarly, the Falls Branch barite-zinc district and the Green County residual barite area (Brobst, 1958, p. 115) might also be reexamined for fluorite in the bedrock deposits. Some similar possibilities exist in the same province in northwestern Georgia and northeastern Alabama.

Fluorite occurs in some abundance in at least two of several small veins in Paleozoic carbonate rocks in the Great Valley extension of the Shenandoah Valley in the triangular area between Waynesboro, Chambersburg, and Mercersburg, Pennsylvania. Geologically these little-known deposits resemble those to the south in Virginia.

Some granitic and volcanic rocks in Virginia and North Carolina contain abundant disseminated fluorite. These igneous rocks may indicate undiscovered fluorite deposits nearby. Notable examples are the granites of Browns Mountain and Beach Mountain in western North Carolina, the Grayson Granodiorite Gneiss and the Mount Rogers Formation in the southern Blue Ridge province of Virginia, and the Petersburg Granite in the eastern Virginia Piedmont (W. C. Overstreet, oral commun., 1972).

In the Piedmont many complex pegmatites are enriched in fluorine minerals, either fluorite or topaz; examples are known in the Rockford area, Alabama, at Amelia, Va., near Sykesville, Md., in the lower Connecticut Valley, at Long Hill, Conn. (p. 79), and in western Maine and eastern New Hampshire. These pegmatitic occurrences are generally not economic.

Contact zones of the Triassic diabases of Virginia, Maryland, Pennsylvania, Connecticut, and Massachusetts, and genetically related magnetite, copper, and silver-lead-zinc deposits, in places contain small quantities of fluorite. Locally, as in the northern part of the Connecticut Valley of Massachusetts, some veins contain sufficient fluorite and barite to be of commercial interest. Felsic and mafic syenites of northern New Jersey also contain disseminated fluorite, and some fluorite has been deposited in adjacent limestones and in the Franklin zinc ore body along the dike contacts.

Fluorite is a common mineral in many of the skarn iron and zinc deposits of the New Jersey Highlands province, which is underlain by Precambrian gneisses, schists, skarns, and marbles (Worl and others, 1973). The highlands extend from west of Reading in eastern Pennsylvania northeastward through New Jersey into southeastern New York in the vicinity of West Point. In no part of this province are commercial fluorite deposits known, but in places fluorite associated with other fluorine-bearing minerals makes major bodies of fluorine-enriched rocks. Such rocks are most abundant in the marble and skarn belts on the northwest side of the highlands.

Barite deposits of the Piedmont province of Virginia, as well as similar deposits in the Kings Mountain district of North Carolina, contain some fluorite (Edmundson, 1938). As fluorite has no doubt been dissolved out of the residual deposits which were mined for barite, the possibilities of fluorite in quantity in the unmined bedrock deposits should be examined.

Fluorite is a common mineral in the high-temperature small hydrothermal deposits of the Pawtucket area of northeastern Rhode Island. These deposits were mined long ago for copper and perhaps gold. They contain—in addition to fluorite—garnet, magnetite, scheelite, molybdenite, chalcopyrite, galena, and sphalerite (Quinn, 1971, p. 58). Similar small quantities of fluorite are found in the gold-silver-lead-zinc-copper deposits of Deer Isle, Penobscot Bay, Maine.

Other potential sources of fluorine in the Central and Eastern United States are topaz, fluorapatite, rare-earth fluocarbonates, and magnesium-iron silicate-fluoride-hydroxides (chondrodite, humite, and norbergite), as well as commercial phosphate deposits.

Topaz most commonly is associated with complex pegmatites, but not in commercial quantities. Such complex pegmatites occur throughout the Appalachian metamorphic belt from Maine to Alabama, and in central Texas. Notable occurrences are the pegmatites in Oxford and Kennebec Counties, Maine, and in New Hampshire on Baldface Mountain in Carroll County, where topaz occurs with beryl and lithium mica. Similar pegmatites are known near Amelia, Va., where very large white crystals of topaz occur in the cores of the Morefield and Rutherford complex pegmatites. Coarse tin-bearing quartz veins that contain topaz are found at Rockford, Coosa County, Ala., and in the Llano uplift of central Texas.

Topaz most commonly is associated with complex granite pegmatites, but not in commercial quantities. Such kyanite, andalusite, pyrophyllite, and diaspore, and in high-temperature veins containing gold, tin, and tungsten minerals. In the Central and Eastern United States large veins and replacement masses of topaz in potentially commercial quantities occur in the Appalachian metamorphic belt, southeast Missouri, and the Llano uplift of Texas.

Appreciable topaz occurs in fissure veins, some consisting of nearly pure, coarse, gray topaz and others consisting of pale-blue topaz crystals, with fluorite and scheelite, on Long Hill near Trumbull in southwestern Connecticut (Crowley, 1968). A similar but less-known occurrence is near Willimantic in eastern Connecticut, where topaz associated with fluorite, columbite, and scheelite is disseminated and in small veins in gneiss.

One of the largest known deposits of topaz is at the Brewer gold mine, 1.5 miles (2.4 km) northwest of Jefferson, Chesterfield County, S.C. More than 700 tons of topaz was mined there before August 1941 (Fries, 1942) for experimental refractory purposes. At the Brewer mine, fine-grained rhyolite tuff and breccia have been metamorphosed to quartz-sericite schist. In places the schist is completely silicified and contains pyrite, gold, and topaz. The topaz forms irregular replacement bodies ranging in width from less than an inch (2.5 cm) to 10 feet (3 m). Some topaz is in large veins and in veinlets; other topaz is disseminated in the schist associated with pyrite and gold (Pardee and Park, 1948, p. 106-111).

The topaz contains 13-14 percent fluorine. The district contains probable reserves of 106,000 tons of rock averaging 15 percent topaz (Fries, 1942) or about 16,000 tons of topaz; some byproduct gold is present. In addition, possible reserves of 194,000 tons of similar grade topaz-bearing rocks might contain 0.05 ounce of gold per ton. The topaz very closely resembles slightly stained vein quartz and can be distinguished only with difficulty from it by a specific gravity greater than that of quartz and by the dull appearance of its weathered surfaces. A placer of topaz occurs downslope from the replacement deposits.

Similar topaz deposits occur with pyrophyllite that is mined at Bowlings Mountain, Granville County, and at Corbett, Caswell County, N.C. At Bowlings Mountain large veins and bodies of massive topaz occur with pyrophyllite and andalusite in Paleozoic sericite schist. At Corbett large veins and disseminations of topaz occur with kyanite in metavolcanic schist. Possibly some of the North Carolina topaz could be recovered profitably from material mined for pyrophyllite if there were a market for the topaz.

Near Rockford, Coosa County, Ala., massive fine-grained topaz occurs in tin greisens and quartz veins in the extensive but not very productive Rockford tin district. A substantial tonnage of topaz could be recovered by concentration.

Very fine grained gray topaz is abundant in greisens in vein walls of several tin, tungsten, and silver-lead veins of the Einstein silver district at Silver mines, southwest of Fredricktown, Madison County, Mo. Fluorite (p. 77) occurs in these veins also, and the two minerals together may constitute a potential fluorine resource especially if recovered as a byproduct of the high-value metallic minerals of the veins.

Fluorine-bearing minerals fluorapatite (nonsedimen-

tary), chondrodite, humite, norbergite, doverite, and bastnaesite, in some places occurring alone but commonly with two or more associated together, form a large-tonnage potential source of fluorine, if the need should arise for such lower-grade materials or if extractive technology improves. A few deposits of these minerals are very large and could supply substantial quantities of fluorine. Recently fluorapatite has been separated and discarded from metalliferous deposits at Mineville, N. Y.; Dover, N. J.; Piney River, Va.; Pea Ridge and Pilot Knob, Mo.; and, to a lesser extent, at Sterling Hill, N. J. Some of the larger deposits and the main minerals present are listed in the following table.

Deposit	Location	Main minerals
New York		
Palmer Hill mines	Ausable	Magnetite, fluorite, fluorapatite.
Mineville iron mines ...	Mineville	Magnetite, fluorite, rare-earth fluorapatite, bastnaesite.
Trembley Mountain.....	St. Lawrence County..	Magnetite, fluorapatite, fluorite.
Tilly Foster mine.....	Brewster, Putnam County.	Magnetite, chondrodite, humite, fluorite, norbergite.
Mahopac mines.....	Mahopac, Putnam County	Do.
O'Niell mine.....	Monroe, Orange County.	Magnetite, fluorapatite, chondrodite.
Amity-Edenville marble quarries.	Edenville, Orange County.	Chondrodite, fluorapatite.
New Jersey		
Rudeville marble quarries.	Rudeville, Sussex County.	Chondrodite, fluorapatite.
McAfee marble quarry	McAfee, Sussex County.	Norbergite, fluorapatite.
Sterling Hill zinc mine.	Sterling Hill	Chondrodite, norbergite, fluorapatite, fluorite, franklinite.
Franklin zinc mine	Franklin.....	Do.
Scrub Oaks iron mine..	Dover	Magnetite, zircon, doverite.
Canfield apatite mine	do.....	Fluorapatite, magnetite.
Hurdtown apatite mine	Hurdtown, Morris County.	Fluorapatite.
Pennsylvania		
Harvey's marble quarry.	Brinton's Ford near West Chester.	Chondrodite.
Virginia		
Nelsonite dikes.....	Piney River, Nelson County.	Ilmenite, apatite.

All these occurrences except Piney River, Va., are in Precambrian skarns. Almost all are in the Adirondack Mountains, in the New Jersey Highland province, or in the Piedmont province. Many others undoubtedly exist and could be located by a detailed field or literature search. Some of the quarry occurrences, such as those in the marble quarry at McAfee, N. J., contain substantial tonnages of minerals such as norbergite that could be quarried, milled, and concentrated on a large scale.

FLUORINE IN PHOSPHATE DEPOSITS

By J. B. CATHCART

Fluorine in sedimentary phosphate deposits is considered here separately as a type distinct from the epigenetic fluorine deposits described in detail in preceding pages. Economic phosphate deposits in the United States are confined to sedimentary phosphorites of Ordovician age in Tennessee and Alabama, of Permian age in the Western States, of Miocene age in North Carolina, Georgia, and South Carolina, and of Miocene and Pliocene ages in Florida (fig. 11). Total reserves are billions of tons of phosphate rock containing 28–38 percent P_2O_5 and more than 3 percent F.

Some fluorine is being produced in Florida as a by-product of manufacture of chemical fertilizer from phosphate rock, and probably much more will be produced in the future (Sweeney, 1971). In January 1971, at the time of a field investigation in Florida by the author, phosphate companies reported that all the phosphate chemical plants there were recovering at least part of the fluorine produced during chemical or thermal treatment of phosphate rock.

Production of phosphate rock in the United States in 1970 was about 37.6 million short tons, a decline for the second straight year. Production data, and tonnages of phosphate rock by major uses, are shown in the following table.

Production and uses of phosphate rock, 1970, in millions of short tons

[Data from U.S. Bureau of Mines Mineral Industry Surveys—Phosphate Rock, Crop Year Annual, November 1970]

PRODUCTION	
Florida (Includes land-pebble, Northern Florida field, and North Carolina).....	29.7
Tennessee (Includes mines in northern Alabama).....	3.0
Western States (Montana, Wyoming, Idaho, Utah, and California).....	4.9
Total	37.6
MAJOR USES	
Chemical or thermal processes in which fluorine is liberated; total 67 percent	
Phosphoric acid (wet process).....	10.1
Electric furnace phosphorus.....	6.8
Triple superphosphate	3.8
Ordinary superphosphate	4.5
Uses in which no fluorine is liberated; total 33 percent	
Exports.....	10.9
All others.....	1.5

Fluorine is liberated during acidulation and electric furnace reduction of phosphate rock as a mixture of polymeric forms of hydrogen fluoride, which attack silica and are released as silicon tetrafluoride gas (Siems, 1951). About two-thirds of the total production of phosphate rock currently is treated chemically or thermally to produce superphosphate and a gaseous effluent that contains fluorine. In 1970, the 25 million tons of

phosphate rock so treated contained about 875,000 short tons of fluorine, assuming an average fluorine content of 3.5 percent in the rock, not all of which was liberated in gaseous effluent. Siems (1951, p. 409) indicated that about one-third of the fluorine is liberated during the manufacture of ordinary superphosphate, and phosphate companies indicate that this figure is approximately correct for the process used in chemical plants in Florida. About two-thirds of the fluorine evidently combines with calcium and does not go off in the gaseous effluent.

The total amount of fluorine currently being produced from phosphate rock is not known. Effluent gases containing fluorine are treated to remove as much of this element as possible (to avoid air pollution), mainly by passing the effluent through powdered limestone. The fluorine in the gas combines with calcium in the limestone to form CaF_2 , but this fluorite was so finely divided that early attempts to recover it were not successful, and the material was discarded as waste. In 1972 several companies were making aluminum fluoride (AlF_3) and artificial cryolite (Na_3AlF_6) from the hydrofluosilicic acid derived from the fluorine in the gas (see p. 84).

Partial chemical analyses of phosphate rock given in the following table represent deposits that were being mined in 1972.

Partial chemical analyses, in percent, of phosphate rock from deposits in the United States

[U.S. Geological Survey analysts: P_2O_5 by G. D. Shipley and Winona Wright, F by Johnnie Gardner, Al_2O_3 by H. H. Lipp and Wayne Mountjoy, Fe and CaO by Violet Merritt and Johnnie Gardner, and SiO_2 by W. D. Goss, H. H. Lipp, and Elsie Rowe]

	Western U.S. ¹	Northern Florida-Southern Georgia ²	North Carolina ³	Florida land-pebble district		Tennessee ⁶
				Pebble ⁴	Concentrate ⁵	
P_2O_5	30.5	33.2	29.7	31.4	34.5	32.8
CaO	44.0	47.0	46.2	46.3	49.7	46.1
F	3.1	3.8	3.6	3.6	3.8	3.6
SiO_2	11.9	6.6	2.9	9.3	5.0	8.6
Al_2O_3	1.7	1.5	.5	1.3	.9	2.2
Fe_2O_3	1.1	.9	.6	1.2	1.0	3.0

¹Average Phosphoria Formation whole-rock analysis (Gulbrandsen, 1966, table 1).

²Average of three samples of concentrate. Analyses by U.S. Geological Survey.

³Average of 40 samples of concentrate. Analyses by phosphate companies and U.S. Geological Survey.

⁴Average of 20 samples of +1 mm material. Analyses by U.S. Geological Survey.

⁵Average of 20 samples of concentrate (-1 mm+0.1 mm). Analyses by U.S. Geological Survey.

⁶Average of 6 samples (Jacob and others, 1933, table 1).

The analyses listed are all averages; those from the western field and from Tennessee are for total rock; the others are for beneficiated material, either flotation concentrate or coarse (pebble) fraction of the land-pebble district of Florida. The average analyses are thought to be representative of the large tonnages shown in the following table of reserves. The fluorine content ranges from 3.1 to 3.8 percent. Individual samples of phosphate rock from the western field contain as much as 4.2 percent F (Gulbrandsen, 1966), and individual samples of Florida concentrate contain as much as 4.3 percent F; the highest grade samples of Florida pebble and of North Carolina concentrate contain about 3.8 percent F.

Reserves of phosphate in the United States total about 10 billion tons as shown in the following table, but these

figures represent only a fraction of the total resources. For example, reserves in Wyoming are listed as 2 billion tons, whereas total resources in Wyoming (Sheldon, 1963, table 20) are about 19 billion tons, and the total resources of phosphate in North Carolina are estimated to be about 10 billion tons. Not all the total resources are minable, and the chemical composition of the material is not well known, but it is certain that the additional resources will contain lower percentages of P_2O_5 and fluorine than the reserves shown.

Phosphate reserves, United States, in millions of long tons

Map No. (Fig. 11)	Reserves	References
Eastern United States		
1. Florida, land-pebble.....	1,000	McKelvey and others (1953).
2. Northern Florida-southern Georgia.	150	Sever, Cathcart, and Patterson (1967); Olson (1966).
3. Northern Georgia-southern South Carolina.	800	Furlow (1969); Heron and Johnson (1966).
5. North Carolina.....	2,000	U.S. Geol. Survey (unpub. data).
6. Tennessee.....	80	Jacob (1953).
Total.....	4,030	
Western United States		
(Includes reserves above entry level and within 100 feet (30 m) below entry level that contain more than 24 percent P_2O_5 . Preliminary figures.)		
7. Idaho.....	2,700	W. C. Gere (written commun., 1972).
8. Wyoming.....	2,000	Do.
9. Utah.....	900	Do.
10. Montana.....	400	Do.
Total.....	6,000	

PRESENT AND FUTURE RESOURCES OF FLUORINE

By D. R. SHAWE, R. G. WORL, R. E. VAN ALSTINE,
and A. V. HEYL

Present and future resources of fluorine in the United States will be examined largely in the light of past exploitation. Until recently fluorspar was virtually the only source of fluorine, and probably will remain the major source in the near future. A relatively minor amount of the fluorine consumed is presently being recovered from processing phosphate rock, and an insignificant amount has been acquired in the past from topaz deposits. Phosphate rock and other byproduct and coproduct sources of fluorine will become increasingly important in the future. Byproduct recovery from fluorspar mining throughout the United States in the past has not been extensive; sulfide concentrates containing mainly lead, zinc, and silver are recovered in some fluorspar operations, and in a few barite is a coproduct.

During the period 1900-70 the United States has changed from the major world producer of fluorspar to about seventh or eighth rank, although its production has generally risen. According to Worl, Van Alstine, and

Shawe (1973, fig. 1), during 1900-20 annual fluorspar production grew from about 18,500 short tons to an average of about 200,000 short tons of CaF_2 ; during 1920-40 it averaged somewhat more than 100,000 short tons; and during 1940-70 average annual production increased from about 300,000 short tons to a maximum of more than 400,000 tons during World War II, and then decreased to about 200,000 tons. Until about 1950 United States production of fluorspar nearly equalled its consumption, but since 1950 consumption has increased dramatically (to about 1,500,000 short tons CaF_2 in 1970) and so domestic production now supplies less than a quarter of the needed fluorspar, and imports have been required for the balance. Furthermore, since 1950 worldwide fluorspar consumption has increased spectacularly to more than 4,500,000 short tons CaF_2 , emphasizing the fact that the United States faces strong competition for foreign supplies of fluorspar.

SUMMARY OF FLUORINE RESOURCES

By R. E. VAN ALSTINE and R. G. WORL

World reserves of fluorspar appear to be adequate to meet fluorine requirements in the foreseeable future. Similarly, United States reserves of fluorspar appear to be adequate for domestic needs for the foreseeable future. Worl, Van Alstine, and Shawe (1973, table 1) have estimated that present world fluorspar reserves outside the United States are about 165,000,000 short tons of crude ore and United States reserves are about 25,000,000 short tons of crude ore (crude ore containing more than 35 percent CaF_2). Hypothetical fluorspar resources (defined as fluorspar that is undiscovered in known districts, or is exploitable only under more favorable economic or technologic conditions—the latter termed “conditional” resources by Brobst and Pratt, 1973, p. 4) have been estimated as almost 530,000,000 short tons in the world outside the United States and as about 45,000,000 short tons in the United States (Worl and others, 1973, table 1). Note that the ratio of identified reserves to hypothetical resources is about 1:2 for the United States whereas it is about 1:3 for foreign deposits, reflecting the fact that United States resources generally have been more extensively explored and exploited than have foreign resources.

Since 1927 several estimates of the fluorspar reserves of the United States have been made by government geologists and mining engineers, and each successive estimate except the 1968 estimate has been a larger figure. In 1927 a reserve of about 5 million tons was estimated for the Illinois-Kentucky district (Iron Age, 1927). In 1937 (Burchard, 1937) this figure was increased to 6 million tons because of the discovery of more replacement deposits in the Cave in Rock area of Illinois (Currier, 1937), and by 1 million tons for western deposits (Burchard, 1933). A joint estimate in 1947 of the U.S. Geological Survey and U.S. Bureau of Mines (Davis and others, 1947) showed 14.7 million tons of fluorspar; a 1952 estimate (Paley, 1952)

gave the reserve at 15 million tons. A more detailed estimate by Van Alstine (U.S. Geol. Survey, 1956) of about 250 fluorspar deposits in the United States showed about 22½ million tons (see the following table); 50 deposits contained 77 percent of the ore reserves. A similar estimate of 21 million tons was made by a geologist in private industry (Sutton, 1954).

Estimated reserves of higher grade fluorspar in the United States as of October 1956, by regions, in terms of short tons of crude ore
[Higher grade fluorspar contains at least 35 percent CaF₂ or equivalent]

Location	Measured and indicated	Inferred	Total	Approximate percent
Illinois, Kentucky ..	8,100,000	4,000,000	12,100,000	54
Colorado, Idaho, Montana, Utah, Wyoming	4,500,000	3,700,000	8,200,000	36
New Mexico, Arizona, Texas....	800,000	700,000	1,500,000	7
California, Nevada, Washington	400,000	350,000	750,000	3
New Hampshire, Tennessee, Alaska .....	.....	10,000	10,000	.....
Total.....	13,800,000	8,760,000	22,560,000	100

In 1968 Van Alstine (U.S. Geol. Survey, 1968) estimated that fluorspar reserves were decreased to about 10 million tons because about 8 million tons of crude ore had been mined, new ore had been discovered, and about 7.5 million tons was transferred to the potential resource category. This quantity was no longer regarded as ore because it became more profitable to use cheaper imports of fluorspar from Mexico, Italy, and Spain than to mine from many of our domestic deposits.

The current estimate of 25,000,000 tons takes into account the improved market situation as well as new fluorspar discoveries (Worl and others, 1973, p. 230).

Nearly all these reserves are believed amenable to beneficiation into acid-grade and metallurgical-grade concentrates. Even ores in which fluorite is intimately intergrown with gangue minerals might be made into concentrates acceptable to the steel industry with the use of sink-float methods, blending of ores or concentrates, and the sintering, nodulizing, or pelletizing of material that meets the chemical specifications of metallurgical-grade fluorspar. In recent years increased use of heavy-media preconcentrators, the pelletizing of flotation concentrates into metallurgical-grade fluorspar, and cost-cutting mining practices have permitted the working of lower grade ores, even though salary scales and material costs have mounted. However, the price of fluorspar has increased above previous prices so that in 1972 all grades averaged about \$70/ton.

Deposits included in the estimate range in size from less than 10,000 tons to at least 500,000 tons. Replacement bodies of fluorspar in the Cave in Rock area, Illinois, average about 9 feet (3 m) in thickness and about 125 feet (38 m) in width. Dimensions of typical veins in New

Mexico are given by Rothrock and others (1946, p. 21).

Potential resources of fluorspar in the United States total about 45 million tons of material containing 15–35 percent CaF₂. Such resources, located chiefly in Illinois, Kentucky, Colorado, Montana, Nevada, New Mexico, Utah, Idaho, Texas, and Alaska, are incompletely known because few marginal or submarginal fluorspar deposits have been explored. A substantial addition to our potential resources resulted from the recent (The Northern Miner, Toronto, Feb. 18, 1971) estimates for the Lost River area, Alaska, where about 10 million tons of material contain 28.5 percent CaF₂ and 0.2 percent Be; 5.3 million tons of this material also contain 0.42 percent Sn and 0.1 percent WO₃ (Sainsbury, 1964b; 1969).

Sedimentary phosphate rock which contains 3–4 percent F constitutes a largely untapped fluorine resource; fluorine has been recovered from phosphate rock only in recent years and it does not yet constitute an appreciable fraction of the market. On the basis of a fluorine content of about 3 percent in marine phosphate rock, the phosphate deposits of Florida, North Carolina, South Carolina, Tennessee, Alabama, Utah, Wyoming, Idaho, and Montana contain about 1/3 billion tons of fluorine in known reserves and about 2 billion tons of fluorine in identified resources. This indicates that marine phosphate rock constitutes by far the United States' and the world's largest fluorine resource.

Phosphate rock soon could become an important source of artificial fluorite, artificial cryolite, fluorine, or fluorine chemicals; two new fluosilicic acid recovery units were put into operation in recent years (Everhart, 1963) by phosphate producers in Florida to supply raw material to a new fluorine chemical plant in the area. Aluminum Company of America has announced (American Metal Market, 1969) construction of a new plant in central Florida to make aluminum fluoride and cryolite from fluosilicic acid from phosphate rock. The production of fluosilicic acid and sodium fluosilicate from phosphate rock for water fluoridation is increasing, especially with greater efforts to reduce air pollution around phosphate plants.

Topaz, found relatively rarely in large concentrations, occurs in probable commercial quantity and grade in at least two localities in the United States. Reserves at the Brewer gold mine in South Carolina were estimated at about 100,000 tons of schist averaging approximately 15 percent topaz and about 1,200 tons of topaz in adjacent placer deposits that contain 1–24 percent topaz. The hypothetical resources at this deposit are estimated at about 800,000 tons of topaz rock. In the Front Range, Colo., a lens in Precambrian gneiss containing about 15 percent topaz was estimated to constitute a reserve of about 600,000 tons of topaz-bearing rock. The hypothetical resources of this topaz-bearing rock are estimated to be about 250,000 tons for every 100 feet (30 m) of depth.

Topaz also occurs in significant amounts (along with fluorite) in the major molybdenum porphyry deposits at

Climax and Henderson, Colo., and Questa, N. Mex. Reserves of fluorine at these deposits have not been estimated but byproduct resources in molybdenum porphyry deposits may constitute as much as several million tons of fluorine.

Bastnaesite in carbonatite at Mountain Pass, Calif., contains a potential fluorine resource. This rare-earth mineral constitutes 5-15 percent of the carbonatite rock and contains about 7 percent fluorine. Based on an estimate of 100 million tons of potential ore resources at Mountain Pass (Olson and others, 1954), nearly 1,000,000 tons of fluorine exists as a potential byproduct of rare-earth extraction.

KNOWN FAVORABLE AREAS FOR FLUORINE EXPLORATION

By D. R. SHAW, R. E. VAN ALSTINE, R. G. WORL, and A. V. HEYL

Search for fluorspar naturally should first be made close to areas where the mineral already has been found. In the productive districts extensions of known fluorspar bodies should be explored along strike and in depth. Additional ore bodies may be found along nearby faults in mineralized districts. Search should be directed especially for stratiform deposits in limestone which have been susceptible to replacement by fluorite; these deposits tend to be large and amenable to large-scale low-cost mining operations, and in the important southern Illinois-western Kentucky district sizable areas having economic potential have not yet been adequately explored. Geochemical investigation of fluorine and related metal anomalies may reveal commercial deposits. Disseminated, lower grade deposits marginal to known bodies may be profitable; some drab, fine-grained, earthy material is difficult to recognize visually as fluorite. An increasingly important source of fluorspar will be as a coproduct from the mining of iron, base-metal, barite, and rare-earth ores. As in Mexico, fluorite may be recovered also from mine dumps and tailings ponds, where it is already ground and partly concentrated. More fluorine analyses should be made routinely on earth materials; thus a new environment for fluorspar may be discovered, as recently described in Tertiary tuffaceous lake beds of Oregon (Sheppard and Gude, 1969).

Most fluorspar districts and localities in the United States remain as areas favorable for further exploration for fluorine resources. The recent discovery of large fluorspar reserves in the Lost River tin district, Alaska, suggests that similar geologic settings along the Rapid River thrust fault elsewhere in the York Mountains are favorable for the occurrence of such carbonate-replacement and pipe-like fluorspar deposits. Other tin districts on the Seward Peninsula, fluorite-mineralized carbonate rocks north of Nome, breccia pipes in the Kigluaik Mountains, and carbonate rocks surrounding alkalic rocks in the Darby Mountains, all offer potential for undiscovered fluorspar deposits. Elsewhere in Alaska, areas where peralkalic

granites are known or where fluorite and topaz are associated with sulfides are favorable for fluorine mineral concentrations. Large fluorine resources are available although currently inaccessible in phosphate rock in northern Alaska.

In the northwestern part of the United States important fluorspar deposits that may have additional potential are the Challis, Big Squaw Creek, and Meyers Cove deposits, Idaho, where fluorite veins occur in dolomite, biotite gneiss, and volcanics and porphyries, respectively; and the Snowbird and Crystal Mountain deposits, Montana, which are pegmatitelike bodies. Numerous other fluorspar deposits associated with volcanic rocks, granitic intrusive rocks, and alkalic rocks, and occurring as pegmatites and disseminated in granite are widespread in the Northwest, specifically in north-central Washington, central and southwestern Idaho, western to central Montana, several areas in Wyoming, and the Black Hills of South Dakota, and the areas of these deposits may be favorable for further exploration for fluorspar resources.

The States of Idaho, Montana, Wyoming, and Utah contain extensive fluorine-bearing phosphate rock; as the distribution of these deposits is well known, large unknown resources of fluorine in phosphate rock are not likely in this region.

In the southwestern part of the United States substantial fluorspar potential is likely in the vicinity of major known districts as well as around districts of only minor production. Additional replacement bodies in limestone in the Fluorine district, Nevada, vein deposits in andesite and rhyolite at Broken Hills, Nev., pipe deposits in carbonate rocks at Spor Mountain, Utah, and veins in volcanic rocks in the Indian Peak Range, Utah may still be found. Throughout much of Nevada, southeastern California, western Utah, and western Arizona numerous minor occurrences of fluorspar in veins, mantos, and pipes in and associated with volcanic rocks, in contact zones and stockworks of hypabyssal and plutonic igneous rocks, in volcanoclastic sediments, and in pegmatites, mark possible targets for exploration for additional fluorspar resources. Of the localities having had only minor fluorspar production, perhaps the most promising are the Quinn Canyon Range, Nev., and the Castle Dome district, Arizona.

The southern Rocky Mountain region of the Western United States in Colorado, New Mexico, western Texas, and southeastern Arizona offers numerous favorable areas where additional fluorspar resources may be discovered in the vicinity of known districts and deposits. Among the deposits characterized as layered and crustified veins in young steep tensional faults and breccia zones occurring in Tertiary volcanic rocks, Paleozoic and Mesozoic sedimentary rocks, and Precambrian silicic igneous and metamorphic rocks are the Northgate and Browns Canyon districts, and deposits at Crystal, Poncha Springs, and Wagon Wheel Gap, Colo., and the Gila, Burro Moun-

tains, Anderson, Gold Hills, Steeple Rock, Sierra Caballos, Zuni Mountains, Fluorite Ridge, and Cooks Peak districts, and deposits at Tonuco, Tortugas Mountain, Bishop Cap, and Sierra Cuchillo, N. Mex. The Sierra Caballos, Sierra Cuchillo, and Tortugas and Bishop Cap deposits in New Mexico and the Eagle Mountains and Christmas Mountains-Corazones Peak districts in Texas also offer potential for manto-type deposits. Significant stockworks, pipelike shoots, and mineralized breccia zones near a middle Tertiary alkalic-silicic stock and containing fluorite, lead, silver, gold, copper, and uranium minerals may still be found in the Jamestown district, Colorado. Other minor occurrences in the Southern Rocky Mountain region also may mark favorable targets for significant undiscovered fluorspar deposits.

Numerous favorable structures in the Illinois-Kentucky district should be explored further for fluorspar. A very large potential for undiscovered deposits still exists in the district. Large low-grade tonnages of fluorspar-mineralized breccia are known near Hicks dome but have not yet been developed.

Elsewhere in the Central and Eastern United States a large potential also exists for the discovery of new fluorine resources in the vicinity of known districts and deposits. All districts and deposits warrant further evaluation for additional resources, but only those with the most promise are mentioned here. The Central Tennessee district may have the largest fluorspar potential in the United States outside of the Illinois-Kentucky district. Breccia fluorspar deposits are known at depth in the Central Tennessee district, and similar deposits may occur in quantity in Ordovician carbonate strata in the Cumberland River vein district in Kentucky. The Central Kentucky district offers good possibilities for undiscovered fluorspar-bearing bedded and breccia deposits and veins. Fluorspar-bearing veins in or near the Rossie district, New York, promise additional potential. The Sweetwater district of eastern Tennessee and similar zinc-barite districts with fluorite throughout the Appalachian Valley and Ridge province between Alabama and Pennsylvania offer fluorspar potential. Districts where fluorite occurs with quartz and in mineralogically more complex veins are known in the Blue Ridge, Piedmont, and New Jersey Highland provinces from Alabama to southern New York and in New England. The most favorable for exploration are the Del Rio district, Tennessee, and the Hot Springs district, North Carolina. Ordovician carbonate rocks in the subsurface in the vicinity of the alkalic intrusive center at Magnet Cove, Ark., may have potential for fluorspar deposits.

Careful geologic mapping where fluorine minerals are known but where adequate geologic maps are not now available will be essential to the development of additional fluorine resources in many areas, for example, as demonstrated at Lost River, Alaska.

SUGGESTIONS FOR LIKELY FUTURE FLUORINE PROVINCES: SPECULATIVE FLUORINE RESOURCES

By D. R. SHAWE, R. G. WORL, and A. V. HEYL

Exploration for and evaluation of speculative fluorine resources—those occurring in districts and environments that are yet to be identified—must be based on knowledge of the geologic environment and the geochemical cycle of fluorine. Geologic mapping in areas not now adequately covered by geologic maps will be essential to evaluation of geologic environment and to successful exploration in such areas. Major geologic parameters that partly define the geologic environment of fluorine mineral deposits are: (1) extensional tectonism related to deep-seated northwesterly and northeasterly conjugate strike-slip structures; (2) high heat flow from the mantle; and (3) magmatism of alkalic affinity characterized by abundant fluorine.

Regions of extensional tectonism are clearly the locales of fluorine mineral deposition in the recent geologic past and presumably have been in older geologic periods. Fluorine deposits of middle Tertiary and younger age are widespread in regions of rift and block faulting also of the same age, and in fact numerous fluorine deposits occur in tension faults in these provinces. Tension fractures in regions of extension appear to be a phenomenon of the upper part of the crust, but no geologic evidence suggests that most of the fluorine itself was derived from the upper part of the crust to be concentrated into tension fractures. Furthermore, the patterns of distribution of fluorine mineral deposits within tensional provinces, that is, the tendency for deposits to form northwesterly and northeasterly alignments, reflects the similar alignment of deeper-seated regional fracture zones of strike-slip character that probably penetrate downward through the crust and constitute the basic structural framework of regions of tension. The general distribution of fluorine mineral belts in extensional provinces thus suggests derivation of fluorine from deep within the crust or from the upper mantle.

Broad regions of high heat flow in the United States coincide with regions of extensional tectonism that is now going on or has occurred in the recent geologic past. Such regions in the Western United States are further distinguished by low seismic velocity in the upper mantle, suggesting abnormally high temperature in the upper mantle that in turn accounts for the high heat flow in the overlying crust. Of course such regions are also characterized by abundant hydrothermal activity, including present-day hot springs. Low seismic velocity in the upper mantle also may indicate a phase change from dunitic to eclogitic composition, implying chemical transfer between mantle and crust, perhaps fractionation of mobile components from the mantle into the crust. Regions of high heat flow thus provide two significant factors essential to the formation of fluorine mineral deposits: an

original source of fluorine (from the upper mantle), and the energy necessary to mobilize fluorine into upper levels of the crust.

The distribution of fluorine-rich igneous rocks of alkalic affinity in the Western United States coincides with regions of extensional tectonism and high heat flow. Again, the ages of the igneous rocks generally coincide with the periods of tectonism and of inferred correlative high heat flow. The foregoing generalization needs elaboration, however, in order to account for the occurrence and distribution of alkalic rocks of different ages and petrologic character with which fluorine mineral deposits are associated. According to one model, during early to middle Tertiary time in the Western United States imbricate subduction took place as a result of differential crustal plate movements, such that an eastward-dipping oceanic plate underrode the continent in two north-trending zones parallel to the continental margin, one underlying the western segment of the Cordillera and the second underlying the present Rocky Mountain trend. In each zone potassium content of the andesitic igneous rocks that were generated by subduction increases eastward (Lipman and others, 1972). Rocks formed along the eastern edge of the Rocky Mountain zone are typically of alkalic character—including trachytes, trachybasalts, phonolites, and other alkalic types—suggesting that their derivation from the subduction zone was at greater depth and under stronger influence of mantle conditions than was the derivation of calc-alkalic types of similar age. Our colleague T. A. Steven suggested orally to us that derivation from a mantle environment also accounted for the higher fluorine content of these rocks and the association with them of fluorine mineral deposits.

In middle Tertiary time extensional tectonism was initiated in the Western United States, marked by a cessation of subduction in the regions of extension (Lipman and others, 1972). Onset of extensional tectonism in the Western United States was marked by transition from andesitic to fundamentally basaltic or basaltic-rhyolitic volcanism (Christiansen and Lipman, 1972). The cause of the generation of fluorine enriched magmas of alkali rhyolite and associated basaltic types during the episode of extension is problematical. We infer it to be likely that such magmas originated in the upper mantle, probably as molten fractions of components with high vapor pressure, that were transported upward into the lower-pressure environment of the crust. According to our belief, distention of the continental lithospheric plate due to differential plate motion resulted in at least incipient dilatant zones in the crust and in the underlying mantle, such that fluorine-enriched magma and fluids moved into the crust from the mantle, and the system of northwesterly and northeasterly strike-slip faults in the crust which implemented the distention and accounted for the block faulting in the upper part of the crust allowed passage of magmas and fluids

from the mantle farther upward through the crust. The suggestion that change in state within the upper mantle resulted from dilatancy due to differential plate motion, rather than the converse, was also proposed by Christiansen and Lipman (1972, p. 276).

Thus we see that although fluorine-enriched magmas are spatially associated with regions of extensional tectonism they are in minor part older than the episode of extension and related to other processes. We believe the significant fact of their origin is that it was influenced by mantle processes, and the material of the magmas was derived from the mantle.

The generalizations above, drawn on the relations observed in the Western United States, can be extrapolated to other regions. We propose, for example, that fluorine-enriched magmas of late Paleozoic age in the Eastern United States were derived from the lower zones of subduction—and hence strongly influenced by the mantle—in a tectonic belt that then bordered the eastern edge of the continent. These magmas were responsible for formation of some but not all of the fluorine mineral deposits in the Appalachian belt of the Eastern United States. Also probably in late Paleozoic time deep-penetrating strike-slip faulting along the 38th parallel of latitude in the Eastern United States (Heyl, 1972) allowed mantle-derived magmas and fluids to move upward into the upper part of the crust in the area of southern Illinois and western Kentucky to account for the extensive development of fluorine mineral deposits there. In Africa, the notable restriction of halogen-rich igneous rocks and fluorine mineral deposits to the rift-valley zones reflects the deep penetration by those structures.

Fluorine apparently is very mobile in the geologic environments described in preceding paragraphs. Fluorine-bearing solutions genetically related to the major geologic parameters specified have permeated country rock, such as altered and mineralized volcanoclastic sediments of the Western United States; have filled fractures in and replaced receptive country rock, as in the Illinois-Kentucky district; and have filled subsidiary fractures in places some distance from igneous activity and major structures, as in many fluorspar districts of the Western United States. Fluorine also moved into other geologic environments associated in time and space with the major geologic parameters to form deposits in the other environments. To use an example from another continent, fluorine mobilized by exhalations or weathering has been transferred from alkalic igneous rocks and carbonatites along African rift structures into lake brines, to be concentrated in evaporites of the rift valleys. Formation of the marine sedimentary carbonate fluorapatite deposits is an important example of reconcentration of fluorine in the supergene cycle.

Older concentrations of fluorine minerals may be reworked virtually in place by younger processes that tend to

mobilize fluorine. In such cases it is impossible to tell on the basis of current knowledge whether younger deposits associated with older deposits consist entirely of "primary" introduced fluorine, or entirely of remobilized older fluorine, or a combination of these. One example is fluorite in the Tertiary gold ores of Cripple Creek, Colo., that are associated with fluorine-rich phonolites and related rocks of Tertiary age (Lindgren and Ransome, 1906, p. 122, 219, 100) and also occur within fluorine-rich Pikes Peak Granite of Precambrian age. Another is fluorite in faults of post-Precambrian age at Mountain Pass, Calif., that are associated with dikes of Tertiary age and also are close to bastnaesite-bearing carbonatite of Precambrian age. These occurrences recall the point emphasized by Peters (1958, p. 667, 683-684) of recurrent mobilization of fluorine from older deposits in fluorine-rich regions.

The major geologic parameters previously discussed define environments and processes in which fluorine was intrinsically available in abnormal amounts in some part of the system, and could be mobilized into concentrations of economic interest. On the other hand, geologic processes in other environments also have acted to concentrate minor (crustal abundance) amounts of fluorine into deposits of economic interest, for example, the precipitation of fluorapatite from seawater.

The geochemical cycle of fluorine can be summarized to show that the inferences are valid regarding the geologic environments in which fluorine is concentrated. Despite the fact that fluorine-rich alkalic rocks appear to be derived from the mantle, and perhaps from deeper in the mantle than its top, rocks irrupted through oceanic crust and clearly derived from the mantle are low in fluorine. In the oceanic environment only magmas that have differentiated in near-surface chambers have tendencies toward alkalic affinities and fluorine enrichment. In the continental environment, however, some fluorine-rich magmas likely were derived from the mantle by a process that resulted in fluorine enrichment, or were differentiated in higher crustal levels to account for fluorine enrichment; some fluorine-rich magmas may have been generated within the crust in a local fluorine-enriched environment, but we do not believe that this was a dominant process, and it probably occurred in a sporadic fashion.

The tendency for high mobility of fluorine within the crust is exhibited by the occurrence of fluorine mineral halos around fluorine-rich intrusives, by the fact that extrusive rocks tend to contain less fluorine than do intrusive rocks, showing a loss of fluorine under lower pressure conditions, and by the fact that volatile components emitted by volcanoes formed from fluorine-rich magmas include substantial fluorine. Geochemical data also show that crystallization of magma tends to drive off fluorine if minerals that can take up fluorine are not formed.

Weathering of rocks at the earth's surface transfers large amounts of fluorine into surface and ground waters; some

of this may be reconcentrated in the near-surface environment, such as in lake brines, but much is transported to the oceans where it is redeposited in sedimentary rocks that generally contain amounts of fluorine comparable to those of igneous rocks. Under special conditions in the oceans large amounts of fluorine become concentrated in sedimentary phosphate deposits, yet these amounts are still only a small percentage of the total fluorine deposited in marine sediments having lower fluorine content.

Metamorphism of sedimentary rocks may cause segregation of fluorine, but evidence of this process is fragmentary. In this respect, Cannon and Pierce (1967) stated that most stratiform lead-zinc-barite-fluorite deposits "in the central lowland of North America contain J-lead of variable isotopic composition, part or all of which originated by mobilization of rock-lead from the Precambrian basement or enclosing marine sedimentary rocks." Whether the source of the fluorine in these deposits is the same as that of the lead is a moot point. Ultrametamorphism of sedimentary and other rocks having concentrations of fluorine may result in development of fluorine-rich magmas and associated fluorine mineral deposits, but again more evidence is needed to prove that such a process has occurred. Negative fluorine-silica correlations in some igneous suites suggest this mechanism as they indicate formation of the igneous rocks by other than magmatic differentiation.

The principles discussed in preceding pages assure us that numerous possibilities exist for new fluorine resources. At present it is impossible to give a quantitative indication of speculative resources other than that they are probably very large.

Generally, prospecting for fluorine mineral deposits in regions of relatively young tectonism and magmatism should have greatest success where regional northwesterly and northeasterly strike-slip structural zones have been intruded by fluorine-rich magmas, or are underlain by large volumes of alkalic volcanic rocks. In regions where older tectonism and magmatism have been obscured by younger geologic events these major geologic features should still be sought. Of course, other deeply penetrating structural zones, particularly major east-west fault zones, where fluorine-rich mantle-derived magmas have been irrupted, also should be favorable locales for fluorine mineral deposits.

In the United States new fluorspar districts may be found northwest of the important Illinois-Kentucky district in carbonate rocks beneath Pennsylvanian rocks, and also northeast of this district toward Ohio and the Michigan basin, beneath Pleistocene cover where fluorite occurrences are known in Silurian and Devonian dolomites. Northern Ohio in the vicinity of Toledo, the Serpent Mound cryptoexplosion structure in southeastern Ohio, southern Indiana west of Louisville, Ky., and the Ste. Genevieve fault zone of southeast Missouri and southern Illinois, may all contain undiscovered fluorspar deposits.

Similarly, the Paleozoic carbonate rocks of central Tennessee and central Kentucky are widely mineralized with fluorite, as shown in recent drilling, and may contain other commercial deposits. Carbonate rocks in subsurface in the vicinity of alkalic intrusives, at Magnet Cove, Ark., may have potential for new fluorspar districts. Large but lower grade stratiform fluorspar deposits in carbonate rocks, like those worked in the United States, France, USSR, and southern Africa, probably will be popular targets for exploration in the United States.

In the Western United States fluorspar deposits undoubtedly underlie parts of the widespread cover of Tertiary and Quaternary sediments and volcanic rocks. Cenozoic calcareous tuffaceous lake beds in the Western United States may be fluorite-bearing, similar to those known in Oregon, Italy, and southern Africa, some of which are of commercial interest. These and other occurrences of this type of fine-grained fluorite may offer potential for large fluorine resources. Some fluorspar deposits of the Western United States are related genetically to areas of silicic-alkalic volcanic rocks, namely the Big Bend igneous subprovince of Texas; the Nacimiento igneous subprovince of Arizona, New Mexico, and Colorado; and the Shoshone igneous province of Nevada, Utah, Idaho, and Montana. Other areas with relatively high fluorine contents in the volcanic rocks might merit further prospecting, especially southeastern Idaho, northwestern Wyoming, and northwestern Utah. In the Thomas Range of west-central Utah, topaz is disseminated in volcanic rocks and commercial fluorspar deposits are distributed around the western periphery of a caldera. Only a third of the caldera is exposed; the remainder, which is covered by rhyolite flows or alluvium, may contain undiscovered deposits (Shawe, 1972, p. B76-B77). A tectonic unit consisting of the Rio Grande trough in New Mexico and its northern extension through Colorado is especially rich in fluorspar deposits and should be explored further. Deposits of syngenetic fluorite associated with gypsum and limestone are reported from Permian marine evaporites in the Bighorn Basin, Wyo. These resemble extensive deposits known in the Permian of USSR; similar evaporites elsewhere in the United States should be investigated for fluorite deposits. Chao and others (1961) reported a new fluorine mineral, neighborite (NaMgF_3), from the Green River Formation, Utah; the economic potential of this mineral here and elsewhere is unknown.

Large deposits of fluorapatite in marine phosphate rock probably exist beneath the sea in Tertiary (and younger?) coastal plain sediments extending east from phosphate deposits in the Carolinas and Florida. Although fluorine is recovered from huge deposits of fluorapatite in alkalic rocks of the USSR, the possibility is not great that deposits of this type may be found and profitably explored in the United States.

Probably millions of tons of topaz-bearing rock are yet to be discovered in widespread metamorphic terranes throughout the United States as well as in still-unknown molybdenum-bearing porphyry deposits. Because cryolite is a rare mineral, it may not be an important source of fluorine; the world's only known commercial deposit of natural cryolite, in Greenland, has been depleted, but similar deposits elsewhere are conceivable. Sodium fluoride has been found in saline lake beds in Tanganyika; it may be present in similar rocks in the United States and may some day be a source of fluorine.

Some brines, volcanic gases, fumaroles, and hot springs with relatively high fluorine contents may suggest fluorine-rich provinces in which deposits of fluorspar, phosphate rock, or other fluorine materials should be sought. Deep-sea sediments, which have more fluorine than most other marine sediments except phosphate rock, contain about 700 ppm F; these types of sediments and sea water itself, which has about 1 ppm F, may be sources of fluorine in the distant future.

Other possible new resources of fluorine, not in the category of speculative resources but classified as conditional resources, are known small but high-grade deposits, and very large probably low-grade multicommodity ores. Numerous high-grade but small deposits of fluorspar, such as those of the Western and Eastern United States might be utilized. To do so would require better techniques than now used of locating and evaluating small pods of fluorspar, and it would also require the use of portable extraction and processing equipment. Even though mining of this type of deposit may be feasible elsewhere in the world it is not likely to be in the United States, however, because of high labor costs and land problems.

Very large low-grade multicommodity ores offer potential fluorine resources. These include deposits in which fluorine, mainly in the form of fluorite, is associated with metallic minerals and those in which it is associated with or contained in other minerals of commercial interest such as barite, bastnaesite, fluorapatite, zeolites, and feldspars. It may be possible in the future to process such multicommodity ores in which no single commodity is of high enough grade to be commercial by itself.

GEOCHEMICAL AND GEOPHYSICAL PROSPECTING METHODS FOR FLUORINE

By W. R. GRIFFITTS and R. E. VAN ALSTINE

Fluorspar deposits have commonly been found by identification of fluorite in outcrops and surficial materials (Grogan, 1960, p. 374; 1964). The surficial materials include soils, anthills, spoil piles of burrowing animals, landslides, and alluvium. The persistence of fluorite during weathering under certain conditions, and the high fluorine content of the mineral, suggest that geochemical methods might be used in prospecting for fluorspar.

Nevertheless, geochemistry has not been used much, in part because of the lack of rapid analytical procedures that could be used to determine the fluorine contents of samples with the necessary reliability and low cost.

Recent work in western North America has shown that fluorite deposits may effectively be sought there by heavy mineral and geochemical techniques. The mineral persists for long distances during transport in the sediment of streams, and can be concentrated therefrom with the gold pan. Thus, the fluorite of the Jamestown district, Colorado, can be detected in stream sediment as far downstream as the South Platte River, a distance of about 35 miles (55 km). In southwestern New Mexico fluorite has similarly been traced in the sediment of dry washes for distances of several miles. The softness and excellent cleavage of the mineral thus do not cause rapid destruction of the grains during transport, nor does the rather low specific gravity prevent its recovery by panning. The occurrence of fluorite in stream and seashore sand was summarized a decade ago by Milner (1962, p. 107).

A systematic heavy-mineral survey near Winston, N. Mex., during 1970 by H. V. Alminas and K. C. Watts (oral commun., 1971; Alminas and others, 1972) showed that fluorite is plentiful in sediment near two major subparallel north-trending faults. Near the intersection of the two faults Ira Young of Socorro, N. Mex., had independently found a large fluorospar deposit. The fluorite that occurs without associated metals or with barite in wash sediments is colorless or pale green, whereas many of the fluorite grains found in sediments with anomalous base-metal contents are purple. It may be possible in some areas therefore to distinguish accessory fluorite of metal deposits from fluorite of higher grade fluorospar deposits. Preliminary chemical analyses show that silts of dry washes contain most fluorine near known fluorospar deposits and where fluorite was panned from the sediment.

Geochemical exploration investigations in the semi-arid Browns Canyon district, Colorado, by Van Alstine (1965) showed that fluorine is found in abnormal concentrations in residual soil directly above and downslope from the principal vein and in alluvium downstream from the vein. The highest anomalous values were about 6–20 times the background value in the soil and 3 times the background in the alluvium. Fluorine thus can have rather low mobility in soils and alluvium in semiarid regions. Van Alstine also pointed out the problems introduced where samples contain abundant biotite and hornblende that increase the background fluorine values—a problem which is avoided by the determining of contents of fluorite instead of fluorine.

Neither heavy mineral nor geochemical prospecting methods for fluorite have been widely applied in fluorospar districts in humid regions. Sang Kyu Yun and others (1970) found geochemical studies of stream sediment and

soils to be useful in prospecting the Hwanggangri region of Korea. Nackowski (1957) found that fluorine was technically unsuited as an indicator element for preliminary exploration for fluorospar in the Illinois-Kentucky district; evidently the humid climate there is unfavorable for fluorine to be highly concentrated in the soil.

Development of thick or well-zoned soils in humid areas is commonly accompanied by removal of fluorine from near-surface materials. Hence, soil samples taken at shallow depth might show subdued anomalies or no anomalies over fluoritic bedrock. Therefore, where soils are well developed, samples should be taken as deep as possible. Soils now being eroded generally have a low fluorine content and may result in stream sediments diluted sufficiently to be ineffective indicators of mineralized rocks. The great concentration of elements of interest that is provided by heavy-mineral separations may be particularly useful in seeking fluorospar.

Friedrich and Plüger (1971) found that lead, zinc, and mercury contents of soils were useful guides in exploring for fluorite in Spain and that mercury was useful in the Wolsendorf district, Germany. They also found that the fluorine content of Black Forest stream water increased by factors of 2 to 5, exceptionally even higher, in flowing through fluorite districts. The use of pathfinder elements instead of fluorine avoids the problems of low-level fluorine analysis but is successful only where the pathfinder metal is consistently associated with fluorospar.

Ineson (1970) found fluorine to be widely and uniformly dispersed in the limestone wallrocks of the Derbyshire district, England, and suggested that the element might be used as a guide to fluorite-galena-barite ore.

Heavy-mineral methods and geochemistry—using zinc as a pathfinder metal—both have been tried in the Illinois-Kentucky district, but without completely overcoming the problems posed by the cover of loess and the segregation of fluorite and sphalerite within separate ore bodies along the mineralized faults (Keighin, 1968).

In the Illinois-Kentucky district silver and antimony are concentrated in galena, and cadmium, gallium, and germanium are in sphalerite (Hall and Heyl, 1968). These elements, as well as elements like mercury or vanadium that may have been introduced with the mineralizing solutions, may be clues to fluorospar bodies. In the Northgate district, Colorado, Worl (U.S. Geol. Survey, 1970) found anomalous molybdenum values as high as 800 ppm centered on one fluorospar vein. If a fluorospar contains uranium minerals—as in the Thomas Range, Utah—scintillation counters or Geiger counters might be helpful in prospecting for fluorospar.

Districtwide studies, intermediate between regional reconnaissance surveys and detailed surveys of individual vein zones, are still needed. It is obvious, of course, that neither geochemical surveys nor heavy-mineral surveys alone can reliably show the presence of economic fluor-

spar deposits, regardless of the scale or detail of the work. Such surveys should be used in conjunction with evaluation of the regional geology and of the known structural and stratigraphic controls of mineralization.

The widespread presence of accessory fluorite in metal deposits of several types can result in fluorine anomalies that are useful primarily as guides to metal ore. J. H. McCarthy and G. B. Gott (oral commun., 1971) observed that a fluorine anomaly correlates with the area of highest gold values in the Cripple Creek gold district, Colorado. A fluorine anomaly extends from the Tertiary rocks into the Precambrian granite and metamorphic rocks north and south of the caldera and closely follows an aeromagnetic high. The fluorine values were mostly between 1,000 and 2,000 ppm; and a few were greater.

J. E. Gair (oral commun., 1971) reported that fluorine anomalies in stream sediments are associated with quartz-fluorite-huebnerite veins in the Hamme tungsten district, North Carolina.

Fluorine forms broad anomalies around tungsten-bearing skarn in the Pyrenees, according to Cachau-Herreillat and Prouhet (1971). These authors therefore concluded that fluorine would be a useful pathfinder element in a regional search for additional tungsten districts. An introduction of fluorine during skarn mineralization is not universal, however. Darling (1971) found that biotite from intrusive rock contains less fluorine near tungsten-bearing skarn than at some distance from such ore.

Geochemical investigation (Kesler and others, 1973) of fluid inclusions in certain igneous rocks, using a simple and economical method of analyzing water-extractable fluoride in rock powders, may be a helpful tool in searching for fluorine-bearing rocks possibly genetically associated with fluorspar deposits. The study by Kesler and others (1973) of nine Laramide granodiorite intrusive complexes in the Greater Antilles and Central America shows fluoride values in intrusives mineralized with base metals to be higher than values in barren intrusives.

In summary, the fluorite contents of concentrates panned from creek and wash sediments are useful in reconnaissance in hilly areas of the semiarid southwest and of humid southern Korea. At some places, as in southwestern New Mexico, a visual examination followed by determination of the total heavy metal content of concentrates may distinguish between fluorspar and fluoritic base-metal deposits. The fluorine contents of soil overlying and downhill from outcrops of faults can be used to determine the presence of fluorite mineralization, as demonstrated by Van Alstine and by Sang and associates.

Bardovskiy and Kolpakov (1961), Bardovskiy (1964), and Ingerman (1965) indicated that fluorite-bearing zones can be effectively distinguished in boreholes by the induced activity method, in which the short-lived isotope F^{20} is activated by neutrons from a polonium-beryllium

source. Percentage of CaF_2 determined from the induced activity logs agrees well with that determined by chemical analysis (error $\pm 1-2$ percent).

Faults in the Illinois fluorspar district (Hubbert, 1944) were studied by the earth-resistivity method. The main faults were clearly shown by anomalies; elsewhere the causes of observed anomalies were not evident. Many of the faults are mineralized with fluorite, but it is impracticable to try to detect minable bodies by direct methods of geophysical prospecting. The refraction seismic method has been used as an indirect means of exploring for fluorspar in southern Illinois (Johnson, 1957). Faults and dikes are detectable by this method but the presence of fluorspar is not. Self-potential investigations also have been made by the Illinois Geological Survey (Weller and others, 1952, p. 36-43).

Alteration zones surrounding the main fluorspar vein at Northgate, Colo., were outlined by induced potential methods, but the veins in unaltered rock were not (Worl, oral commun., 1972).

REFERENCES

- Abramovich, Yu. M., and Nechayev, Yu. A., 1960, Authigenic fluorite in Kungurian deposits of the Permian Priurals [in Russian]: *Akad. Nauk SSSR Doklady*, v. 135, no. 2, p. 414-415; English translation in *Acad. Sci. USSR Doklady, Earth Sci. Sec.*, v. 135, nos. 1-6, p. 1288-1289, 1961.
- Abreu, S. F., 1960, Recursos minerais do Brasil—Materials não metálicos, V. 1: Rio de Janeiro, Inst. Nac. de Tecnologia, 471 p.
- Albritton, C. C., Jr., and Smith, J. F., Jr., 1965, Geology of the Sierra Blanca area, Hudspeth County, Texas: U.S. Geol. Survey Prof. Paper 479, 131 p.
- Allen, R. D., 1952, Variations in chemical and physical properties of fluorite: *Am. Mineralogist*, v. 37, nos. 11-12, p. 910-930.
- Alminas, H. V., Watts, K. C., and Siems, D. L., 1972, Maps showing fluorite distribution in the Winston and Chise quadrangles and in the west part of the Priest Tank quadrangle, Sierra County, New Mexico: U.S. Geol. Survey Misc. Field Studies Map MF-402.
- American Metal Market, 1969, Fluorides plant set: p. 11, Oct. 8.
- Amos, D. H., 1966, Geologic map of the Golconda quadrangle, Kentucky-Illinois, and the part of the Brownfield quadrangle in Kentucky: U.S. Geol. Survey Geol. Quad. Map GQ-546.
- 1967, Geologic map of part of the Smithland quadrangle, Livingston County, Kentucky: U.S. Geol. Survey Geol. Quad. Map GQ-657.
- Amstutz, G. C., and Park, W. C., 1967, Stylolites of diagenetic age and their role in the interpretation of the southern Illinois fluorspar deposits [with German abs.]: *Mineralium Deposita*, v. 2, no. 1, p. 44-53.
- Anderson, A. L., 1954a, Fluorspar deposits near Meyers Cove, Lemhi County, Idaho: Idaho Bur. Mines and Geology Pamph. 98, 34 p.
- 1954b, A preliminary report on the fluorspar mineralization near Challis, Custer County, Idaho: Idaho Bur. Mines and Geology Pamph. 101, 13 p.
- 1959, Geology and mineral resources of the North Fork quadrangle, Lemhi County, Idaho: Idaho Bur. Mines and Geology Pamph. 118, 92 p.
- Anderson, A. L., and Van Alstine, R. E., 1964, Mineral resources—Fluorspar in Mineral and water resources of Idaho: U.S. 88th Cong. 2d sess., Comm. Print, p. 79-84.
- Archbold, N. L., 1966, Industrial mineral deposits of Mineral County Nevada: Nevada Bur. Mines Rep. 14, 32 p.

- Armstrong, R. L., 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range Province, western Utah, eastern Nevada, and vicinity, U.S.A.: *Geochim. et Cosmochim. Acta*, v. 34, no. 2, p. 203-232.
- Bancroft, Howland, 1914, The ore deposits of northeastern Washington, including a section on The Republic mining district, by Waldemar Lindgren and Howland Bancroft: U.S. Geol. Survey Bull. 550, 215 p.
- Bannerman, H. M., 1941, The fluorite deposits of Cheshire County, New Hampshire: New Hampshire Planning and Devel. Comm. Mineral Resources Survey, pt. 5, 11 p.
- Bardill, J. D., 1946, Exploration of the Stoddard fluorite mine, Cheshire County, New Hampshire: U.S. Bur. Mines Rept. Inv. 3937, 6 p.
- Bardovskiy, V. Ya., 1964, Quantitative determination of fluorspar by the method of induced activity [in Russian]: *Razved. Geofizika*, no. 1, p. 66-72.
- Bardovskiy, V. Ya., and Kolpakov, A. V., 1961, Use of the method of induced activity for bringing out ore zones in boreholes in fluorite deposits: *Ministerstvo Geologii i Okhrany Nedr SSSR, Voprosy Rudnoy Geofiziki*, no. 3, p. 85-86.
- Barrell, Joseph, 1907, Geology of the Marysville mining district, Montana, a study of igneous intrusion and contact metamorphism: U.S. Geol. Survey Prof. Paper 57, 178 p.
- Barth, T. F. W., 1947, On the geochemical cycle of fluorine: *Jour. Geology*, v. 55, no. 5, p. 420-426.
- Baxter, J. W., and Desborough, G. A., 1965, Areal geology of the Illinois fluorspar district—Pt. 2, Karbers Ridge and Rosiclare quadrangles: *Illinois Geol. Survey Circ.* 385, 40 p.
- Baxter, J. W., Desborough, G. A., and Shaw, C. W., 1967, Areal geology of the Illinois fluorspar district—Pt. 3, Herod and Shetlerville quadrangles: *Illinois Geol. Survey Circ.* 413, 41 p.
- Baxter, J. W., Potter, P. E., and Doyle, F. L., 1963, Areal geology of the Illinois fluorspar district—Pt. 1, Saline mines, Cave in Rock, Dekoven, and Repton quadrangles: *Illinois Geol. Survey Circ.* 342, 43 p.
- Becraft, G. E., and Weis, P. L., 1963, Geology and mineral deposits of the Turtle Lake quadrangle, Washington: U.S. Geol. Survey Bull. 1131, 73 p.
- Blackwell, D. D., 1971, Heat flow in U.S. National Report, 1967-1971, 15th General Assembly, IUGG: EOS (Am. Geophys. Union Trans.), v. 52, no. 5, p. IUGG 135-IUGG 139.
- Blanchard, F. N., 1966, Thermoluminescence of fluorite and age of deposition: *Am. Mineralogist*, v. 51, nos. 3-4, p. 474-485.
- Bradbury, J. C., 1962, Trace elements, rare earths, and chemical composition of southern Illinois igneous rocks: *Illinois Geol. Survey Circ.* 330, 12 p.
- Bradbury, J. C., Finger, G. C., and Major, R. L., 1968, Fluorspar in Illinois: *Illinois Geol. Survey Circ.* 420, 64 p.
- Bradbury, J. C., Ostrom, M. E., and McVicker, L. D., 1955, Preliminary report on uranium in Hardin County, Illinois: *Illinois Geol. Survey Circ.* 200, 21 p.
- Brecke, E. A., 1962, Ore genesis of the Cave-in-Rock fluorspar district, Hardin County, Illinois: *Econ. Geology*, v. 57, no. 4, p. 499-535.
- 1964a, Barite zoning in the Illinois-Kentucky fluorspar district: *Econ. Geology*, v. 59, no. 2, p. 299-302.
- 1964b, A possible source of solutions of the Illinois-Kentucky fluorspar district: *Econ. Geology*, v. 59, no. 7, p. 1293-1297.
- 1967, Sulfide and sulfur occurrences of the Illinois-Kentucky fluorspar district: *Econ. Geology*, v. 62, no. 3, p. 376-389.
- Brobst, D. A., 1958, Barite resources of the United States: U.S. Geol. Survey Bull. 1072-B, p. 67-130.
- Brobst, D. A., Pinckney, D. M., and Sainsbury, C. L., 1971, Geology and geochemistry of the Sinuk River barite deposit, Seward Peninsula, Alaska, in *Geological Survey research 1971*: U.S. Geol. Survey Prof. Paper 750-D, p. D1-D8.
- Brobst, D. A., and Pratt, W. P., eds., 1973, United States mineral resources: U.S. Geol. Survey Prof. Paper 820, 722 p.
- Brown, J. S., 1970, Mississippi Valley type lead-zinc ores—a review and sequel to the "Behre Symposium" [with French abs.]: *Mineralium Deposita*, v. 5, no. 2, p. 103-119.
- Brown, J. S., Emery, J. A., and Meyer, P. A., Jr., 1954, Explosion pipe in test well on Hicks Dome, Hardin County, Illinois: *Econ. Geology*, v. 49, no. 8, p. 891-902.
- Buddington, A. F., 1923, Mineral deposits of the Wrangell district: U.S. Geol. Survey Bull. 739-B, p. 51-75.
- 1934, Geology and mineral resources of the Hammond, Antwerp, and Lowville quadrangles, with a chapter on the Paleozoic rocks of the Lowville quadrangle, by Rudolf Ruedemann: New York State Mus. Bull. 296, 251 p.
- Burchard, E. F., 1933, Fluorspar deposits in Western United States: New York, Am. Inst. Mining Metall. Engineers, Tech. Pub. 500, 26 p.
- 1937, Fluorspar and cryolite, Chap. 15, in *Industrial minerals and rocks (nonmetallics other than fuels)*: New York, Am. Inst. Mining Metall. Engineers, p. 283-302.
- Cachau-Herreillat, F., and Prouhet, J. P., 1971, The utilization of metalloids (arsenic, phosphorus, fluorine) as pathfinders for skarn tungsten deposits in the Pyrénées, in *Geochemical exploration—Internat. Geochem. Explor. Symposium, 3d, Toronto 1970, Proc.: Canadian Inst. Mining Metallurgy Spec. Vol. 11*, p. 117-120.
- Callaghan, Eugene, and Lemmon, D. M., 1941, Tungsten resources of the Blue Wing district, Lemhi County, Idaho: U.S. Geol. Survey Bull. 931-A, p. 1-21.
- Cannon, R. S., and Pierce, A. P., 1967, Isotopic varieties of lead in stratiform deposits, in *Genesis of stratiform lead-zinc-barite-fluorite deposits (Mississippi Valley type deposits)—A symposium*, New York, 1966: *Econ. Geology Mon.* 3, p. 427-433.
- Carpenter, Roy, 1969, Factors controlling the marine geochemistry of fluorine: *Geochim. et Cosmochim. Acta*, v. 33, no. 10; p. 1153-1167.
- Chao, E. C. T., Evans, H. T., Jr., Skinner, B. J., and Milton, Charles, 1961, Neighborite, NaMgF₃, a new mineral from the Green River Formation, South Uray, Utah: *Am. Mineralogist*, v. 46, nos. 3-4, p. 379-393.
- Choate, Raoul, 1962, Geology and ore deposits of the Stanley area: Idaho Bur. Mines and Geology Pamph. 126, 122 p.
- Christiansen, R. L., and Lipman, P. W., 1972, Late Cenozoic [Pt.] 2 of Cenozoic volcanism and plate-tectonic evolution of the Western United States: *Royal Soc. London Philos. Trans., ser. A*, v. 271, no. 1213, p. 249-284.
- Clabaugh, S. E., and Sewell, C. R., 1964, Snowbird deposit, Montana—A carbonatite "pegmatite"?, in *Abstracts for 1963*: *Geol. Soc. America Spec. Paper* 76, p. 268-269.
- Clark, S. K., and Royds, J. S., 1948, Structural trends and fault systems in Eastern Interior Basin [U.S.]: *Am. Assoc. Petroleum Geologists Bull.*, v. 32, no. 9, p. 1728-1749.
- Clegg, K. E., and Bradbury, J. C., 1956, Igneous intrusive rocks in Illinois and their economic significance: *Illinois Geol. Survey Rept. Inv.* 197, 19 p.
- Coats, R. R., 1956, Distribution of uranium and certain other trace elements in felsic volcanic rocks of Cenozoic age in the Western United States, in Page, L. R., Stocking, H. E., and Smith, H. B., compilers, *Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy*, Geneva, Switzerland, 1955: U.S. Geol. Survey Prof. Paper 300, p. 75-78.
- Coats, R. R., Goss, W. D., and Rader, L. F., 1963, Distribution of fluorine in unaltered silicic volcanic rocks of the western conterminous United States: *Econ. Geology*, v. 58, no. 6, p. 941-951.
- Cobb, E. H., 1964, Industrial minerals and construction materials occurrences in Alaska: U.S. Geol. Survey Mineral Inv. Resource Map MR-41.

- Cornwall, H. R., and Kleinhampl, F. J., 1961, Geology of the Bare Mountain quadrangle, Nevada: U.S. Geol. Survey Geol. Quad Map GQ-157.
- , 1964, Geology of Bullfrog quadrangle and ore deposits related to Bullfrog Hills caldera, Nye County, Nevada, and Inyo County, California: U.S. Geol. Survey Prof. Paper 454-J, 25 p.
- Correns, C. W., 1956, The geochemistry of the halogens, [Chap.] 7, in V. 1 of Ahrens, L. H., Rankama, Kalervo, and Runcorn, S. K., eds., *Physics and chemistry of the earth*: New York, McGraw-Hill Co., Inc., p. 181-233.
- Cox, D. C., 1945, General features of Colorado fluorspar deposits: Colorado Sci. Soc. Proc., v. 14, no. 6, p. 263-285.
- , 1954, Fluorspar deposits near Meyers Cove, Lemhi County, Idaho: U.S. Geol. Survey Bull. 1015-A, p. 1-21.
- Cox, D. P., 1970, Lead-zinc-silver deposits related to the White Mountain Plutonic Series in New Hampshire and Maine: U.S. Geol. Survey Bull. 1312-D, 18 p.
- Crosby, J. W., 3d, and Hoffman, S. R., 1951, Fluorspar in California: California Jour. Mines and Geology, v. 47, no. 4, p. 619-638.
- Crowley, W. P., 1968, The bedrock geology of the Long Hill and Bridgeport quadrangles, with maps: Connecticut Geol. and Nat. History Survey Quad. Rept. 24, 81 p.
- Cummings, J. B., 1946, Exploration of the Packard fluorspar property, Gila County, Arizona: U.S. Bur. Mines Rept. Inv. 3880, 7 p.
- Currier, L. W., 1923, Fluorspar deposits of Kentucky; a description and interpretation of the geologic occurrence and industrial importance of Kentucky fluorspar: Kentucky Geol. Survey, ser. 6, v. 13, 198 p.
- , 1937, Geologic factors in the interpretation of fluorspar reserves in the Illinois-Kentucky field: U.S. Geol. Survey Bull. 886-B, p. 5-14.
- Currier, L. W., and Wagner, O. E., Jr., 1944, Geology of the Cave In Rock district, Pt. 1, of Geological and geophysical survey of fluorspar areas in Hardin County, Illinois: U.S. Geol. Survey Bull. 942, p. 1-72.
- Darling, R., 1971, Preliminary study of the distribution of minor and trace elements in biotite from quartz monzonite associated with contact-metasomatic tungsten-molybdenum-copper ore, California, U.S.A., in *Geochemical exploration—Internat. Geochem. Explor. Symposium*, 3d, Toronto, 1970, Proc.: Canadian Inst. Mining and Metallurgy Spec. Vol. 11, p. 315-322.
- Davis, H. W., Johnson, A. C., and Williams, J. S., 1947, Fluorspar, in *Investigation of the factors affecting minerals, fuels, forestry, and reclamation projects*: U.S. 80th Cong., 1st sess., Senate hearings before subcommittee on Public Lands, p. 242-245.
- Deans, T., 1966, Economic mineralogy of African carbonatites, in Tuttle, O. F., and Gittins, J., eds., *Carbonatites*: New York, Interscience Publishers, p. 385-416.
- Deans, T., Sukhweswala, R. N., Sethna, S. F., and Viladkar, S. G., 1972, Metasomatic feldspar rocks (potash fenites) associated with the fluorite deposits and carbonatites of Amba Dongar, Gujarat, India: *Inst. Mining and Metallurgy Trans., Sec. B*, v. 81, Bull. 783, p. B1-B9.
- De Koster, G. R., 1960, Petrology of the (Permian) Phosphoria Formation carbonates, eastern Big Horn Basin, Wyoming: Ames, Iowa State Univ. Sci. and Technology M. S. thesis, 112 p.
- Drewes, Harald, 1963, Geology of the Funeral Peak quadrangle, California, on the east flank of Death Valley: U.S. Geol. Survey Prof. Paper 413, 78 p.
- , 1967, Geology of the Connors Pass quadrangle, Schell Creek Range, east-central Nevada: U.S. Geol. Survey Prof. Paper 557, 93 p.
- Eakin, H. M., 1915, Iron-ore deposits near Nome: U.S. Geol. Survey Bull. 622-I, p. 361-365.
- Earl, K. M., 1959, John Burdette barite-fluorite deposit, Garrard County, Kentucky: U.S. Bur. Mines Rept. Inv. 5480, 14 p.
- Edmundson, R. S., 1938, Barite deposits of Virginia: Virginia Geol. Survey Bull. 53, 85 p.
- Elston, W. E., 1970, Volcano-tectonic control of ore deposits, southwestern New Mexico, in *Guidebook of the Tyrone-Big Hatchet Mountains-Florida Mountains region—New Mexico Geol. Soc. 21st Field Conf.*, 1970: New Mexico Bur. Mines and Mineral Resources, p. 147-153.
- Espenshade, G. H., 1947, Tungsten deposits of Vance County, North Carolina, and Mecklenburg County, Virginia: U.S. Geol. Survey Bull. 948-A, p. 1-17.
- Espenshade, G. H., and Potter, D. B., 1960, Kyanite, sillimanite, and andalusite deposits of the southeastern States: U.S. Geol. Survey Prof. Paper 336, 121 p.
- Everhart, D. L., 1963, Fluorine reserves and potential recovery from domestic phosphate rock [abs.]: *Mining Eng.*, v. 15, no. 11, p. 56.
- Fenner, C. N., 1933, Pneumatolytic processes in the formation of minerals and ores, in *Ore deposits of the Western States* (Lindgren volume): New York, Am. Inst. Mining Metall. Engineers, p. 58-106.
- Ferguson, H. W., and Jewell, W. B., 1951, Geology and barite deposits of the Del Rio district, Cocke County, Tennessee: Tennessee Div. Geology Bull. 57, 235 p.
- Fleischer, Michael, 1969, The lanthanide elements in fluorite: *Indian Mineralogist*, v. 10, p. 36-39.
- Fleischer, Michael, and Robinson, W. O., 1963, Some problems of the geochemistry of fluorine, in *Studies in analytical geochemistry*: Royal Soc. Canada Spec. Pub. 6, p. 58-75.
- Freas, D. H., 1961, Temperatures of mineralization by liquid inclusions, Cave-In-Rock fluorspar district, Illinois: *Econ. Geology*, v. 56, no. 3, p. 542-556.
- Friedrich, G. H., and Plüger, W. L., 1971, Geochemical prospecting for barite and fluorite deposits, in *Geochemical exploration—Internat. Geochem. Explor. Symposium*, 3d, Toronto 1970, Proc.: Canadian Inst. Mining and Metallurgy Spec. Vol. 11, p. 151-156.
- Fries, Carl, Jr., 1942, Topaz deposits near the Brewer mine, Chesterfield County, South Carolina: U.S. Geol. Survey Bull. 936-C, p. 59-78.
- Fuge, R., and Power, G. M., 1969, Chlorine and fluorine in granitic rocks from S. W. England: *Geochim. et Cosmochim. Acta*, v. 33, no. 7, p. 888-893.
- Furlow, J. W., 1969, Stratigraphy and economic geology of the eastern Chatham County phosphate deposit: Georgia Geol. Survey Bull. 82, 40 p.
- Gault, H. R., Rossman, D. L., Flint, G. M., Jr., and Ray, R. G., 1953, Some zinc-lead deposits of the Wrangell district, Alaska: U.S. Geol. Survey Bull. 998-B, p. 15-58.
- Gerasimovskiy, V. I., and Savinova, Ye. N., 1969, Fluorine contents of volcanic rocks in the Rift zone of East Africa [in Russian]: *Geokhimiya*, no. 12, p. 1466-1471; English translation in *Geochemistry Internat.*, v. 6, p. 1124-1128, 1969.
- Gilbert, G. K., 1928, Studies of Basin-Range structure: U.S. Geol. Survey Prof. Paper 153, 92 p.
- Gillerman, Elliot, 1952, Fluorspar deposits of Burrow Mountains and vicinity, New Mexico: U.S. Geol. Survey Bull. 973-F, p. 261-289.
- , 1953, Fluorspar deposits of the Eagle Mountains, Trans-Pecos, Texas: U.S. Geol. Survey Bull. 987, 98 p.
- , 1964, Mineral deposits of western Grant County, New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 83, 213 p.
- Gilluly, James, 1963, The tectonic evolution of the western United States: *Geol. Soc. London Quart. Jour.*, v. 119, pt. 2, no. 474, p. 133-174.
- Gilluly, James, and Masursky, Harold, 1965, Geology of the Cortez quadrangle, Nevada, with a section on Gravity and aeromagnetic surveys, by D. R. Mabey: U.S. Geol. Survey Bull. 1175, 117 p.

- Goddard, E. N., 1946, Fluorspar deposits of the Jamestown district, Boulder County, Colorado: *Colorado Sci. Soc. Proc.*, v. 15, no. 1, 47 p.
- 1966, Geologic map and sections of the Zuni Mountains fluorspar district, Valencia County, New Mexico: U.S. Geol. Survey Misc. Geol. Inv. Map I-454.
- Goldring, E. D., 1942, An occurrence of ilsemannite [Colorado]: *Am. Mineralogist*, v. 27, no. 10, p. 717-719.
- Grametbauer, A. B., 1959, Selected bibliography of andalusite, kyanite, sillimanite, dumortierite, topaz, and pyrophyllite in the United States: U.S. Geol. Survey Bull. 1019-N, p. 973-1046.
- Griffitts, W. R., and Powers, H. A., 1963, Beryllium and fluorine content of some silicic volcanic glasses from Western United States, in *Short papers in geology and hydrology*: U.S. Geol. Survey Prof. Paper 475-B, p. B18-B19.
- Grogan, R. M., 1960, Fluorspar and cryolite, in *Industrial minerals and rocks (nonmetallics other than fuels)* [3d ed.]: New York, Am. Inst. Mining Metall. Petroleum Engineers, p. 363-382.
- 1964, Finding sources of fluorine [abs.]: *Mining Eng.*, v. 16, no. 1, p. 65.
- Grogan, R. M., and Bradbury, J. C., 1967, Origin of the stratiform fluorite deposits of southern Illinois, in *Genesis of stratiform lead-zinc-barite-fluorite deposits (Mississippi Valley type deposits)—A symposium*, New York, 1966: *Econ. Geology Mon.* 3, p. 40-51.
- 1968, Fluorite-zinc-lead deposits of the Illinois-Kentucky mining district, in Ridge, J. D., ed., *Ore deposits of the United States, 1933-1967 (Graton-Sales Volume)*, V. 1: New York, Am. Inst. Mining, Metall. and Petroleum Engineers, p. 370-399.
- Grogan, R. M., and Shrode, R. S., 1952, Formation temperatures of southern Illinois bedded fluorite as determined from fluid inclusions: *Am. Mineralogist*, v. 37, nos. 7-8, p. 555-566.
- Guccione, Eugene, 1972, What's going on in the fluorspar industry: *Eng. and Mining Jour.*, v. 173, no. 12, p. 64-73.
- Gulbrandsen, R. A., 1966, Chemical composition of phosphorites of the Phosphoria Formation: *Geochim. et Cosmochim. Acta*, v. 30, no. 8, p. 769-778.
- Gulbrandsen, R. A., and Reeser, D. W., 1969, An occurrence of Permian manganese nodules near Dillon, Montana, in *Geological Survey research 1969*: U.S. Geol. Survey Prof. Paper 650-C, p. C49-C57.
- Hall, W. E., and Friedman, Irving, 1963, Composition of fluid inclusions, Cave-in-Rock fluorite district, Illinois, and Upper Mississippi Valley zinc-lead district: *Econ. Geology*, v. 58, no. 6, p. 886-911.
- Hall, W. E., and Heyl, A. V., 1968, Distribution of minor elements in ore and host rock, Illinois-Kentucky fluorite district and Upper Mississippi Valley zinc-lead district: *Econ. Geology*, v. 63, no. 6, p. 655-670.
- Hamilton, Warren, 1972, The Hallett volcanic province, Antarctica: U.S. Geol. Survey Prof. Paper 456-C, 62 p.
- Hardin, G. C., Jr., 1955, Babb fault system, Crittenden and Livingston Counties, in Pt. 1 of *Fluorspar deposits in western Kentucky*: U.S. Geol. Survey Bull. 1012-B, p. 7-37.
- Hardin, G. C., Jr., and Thurston, W. R., 1945, Celestite from Livingston County, Kentucky: *Am. Mineralogist*, v. 30, nos. 9-10, p. 639-640.
- Hardin, G. C., Jr., and Trace, R. D., 1959, Geology and fluorspar deposits, Big Four fault system, Crittenden County, Kentucky: U.S. Geol. Survey Bull. 1042-S, p. 699-724.
- Hatmaker, Paul, and Davis, H. W., 1938, The fluorspar industry of the United States with special reference to the Illinois-Kentucky district: *Illinois Geol. Survey Bull.* 59, 128 p.
- Hawley, C. C., 1969, Geology and beryllium deposits of the Lake George (or Badger Flats) beryllium area, Park and Jefferson Counties, Colorado: U.S. Geol. Survey Prof. Paper 608-A, 44 p.
- Hawley, C. C., Huffman, Claude, Jr., Hamilton, J. C., and Rader, L. F., Jr., 1966, Geologic and geochemical features of the Redskin Granite and associated rocks, Lake George beryllium area, Colorado, in *Geological Survey research 1966*: U.S. Geol. Survey Prof. Paper 550-C, p. C138-C147.
- Herbert, Paul, Jr., and Young, R. S., 1956, Sulfide mineralization in the Shenandoah Valley of Virginia: *Virginia Div. Geology Bull.* 70, 58 p.
- Heron, S. D., Jr., and Johnson, H. S., Jr., 1966, Clay mineralogy, stratigraphy, and structural setting of the Hawthorn Formation, Coosawhatchie district, South Carolina: *Southeastern Geology*, v. 7, no. 2, p. 51-63.
- Herreid, Gordon, 1966, Preliminary geology and geochemistry of the Sinuk River area, Seward Peninsula, Alaska: *Alaska Div. Mines and Minerals Geol. Rept.* 24, 19 p.
- Herrin, Eugene, and Taggart, James, 1962, Regional variation in Pn velocity and their effect on the location of epicenters: *Seismol. Soc. America Bull.*, v. 52, no. 5, p. 1037-1046.
- Hewett, D. F., 1964, Veins of hypogene manganese oxide minerals in the southwestern United States: *Econ. Geology*, v. 59, no. 8, p. 1429-1472.
- Hewett, D. F., and Fleischer, Michael, 1960, Deposits of manganese oxides: *Econ. Geology*, v. 55, no. 1, p. 1-55.
- Hewett, D. F., Fleischer, Michael, and Conklin, Nancy, 1963, Deposits of manganese oxides—Supplement: *Econ. Geology*, v. 58, no. 1, p. 1-51.
- Heyl, A. V., 1967, Some aspects of genesis of stratiform zinc-lead-barite-fluorite deposits in the United States, in *Genesis of stratiform lead-zinc-barite-fluorite deposits (Mississippi Valley type deposits)—A symposium*, New York, 1966: *Econ. Geology Mon.* 3, p. 20-29.
- 1968, Minor epigenetic, diagenetic, and syngenetic sulfide, fluorite, and barite occurrences in the central United States: *Econ. Geology*, v. 63, no. 6, p. 585-594.
- 1969, Some aspects of genesis of zinc-lead-barite-fluorite deposits in the Mississippi Valley, U.S.A.: *Inst. Mining and Metallurgy Trans.*, Sec. B, v. 78, Bull. 756, p. B148-B160.
- 1972, The 38th parallel lineament and its relationship to ore deposits: *Econ. Geology*, v. 67, no. 7, p. 879-894.
- Heyl, A. V., and Brock, M. R., 1961, Structural framework of the Illinois-Kentucky mining district and its relation to mineral deposits, in *Short papers in the geologic and hydrologic sciences*: U.S. Geol. Survey Prof. Paper 424-D, p. D3-D6.
- Heyl, A. V., Brock, M. R., Jolly, J. L., and Wells, C. E., 1965, Regional structure of the southeast Missouri and Illinois-Kentucky mineral districts: U.S. Geol. Survey Bull. 1202-B, 20 p. [1966].
- Heyl, A. V., Delevaux, M. H., Zartman, R. E., and Brock, M. R., 1966, Isotopic study of galenas from the upper Mississippi Valley, the Illinois-Kentucky, and some Appalachian Valley mineral districts: *Econ. Geology*, v. 61, no. 5, p. 933-961.
- Horton, R. C., 1961, An inventory of fluorspar occurrences in Nevada: *Nevada Bur. Mines Rept.* 1, 31 p.
- Hubbert, M. K., 1944, An exploratory study of faults in the Cave In Rock and Rosiclare districts by the earth-resistivity method, Pt. 2, of *Geological and geophysical survey of fluorspar areas in Hardin County, Illinois*: U.S. Geol. Survey Bull. 942, p. 73-147.
- Industrial Minerals, 1970, Steelmakers face possible shortages of fluorspar: *Industrial Minerals*, no. 33, p. 9-13, June.
- 1970, Europe and N. America (excluding Mexico), Pt. 1 of *World fluorspar industry*: *Industrial Minerals*, no. 33, p. 15-29, June.
- 1970, Latin America, Africa and the Far East, Pt. 2 of *World fluorspar industry*: *Industrial Minerals*, no. 34, p. 21-28, July.
- 1970, The adequacy of acid-grade fluorspar supplies questioned: *Industrial Minerals*, no. 34, p. 11-19, July.
- Ineson, P. R., 1970, Trace-element aureoles in limestone wallrocks adjacent to fissure veins in the Eyam area of the Derbyshire ore field: *Inst. Mining and Metallurgy Trans.*, Sec. B, v. 79, Bull. 768, p. B238-B245.

- Ingerman, V. G., 1965, Detecting fluorite mineralization in borehole sections by the activation gamma-logging method: *Razved. Geofizika*, no. 7, p. 78-80.
- Iron Age, 1927, p. 1835, June 23.
- Jacob, K. D., 1953, Phosphate resources and processing facilities, in Jacob, K. D., ed., *Fertilizer technology and resources in the United States*: New York, Academic Press, Inc., p. 117-165.
- Jacob, K. D., Hill, W. L., Marshall, H. L., and Reynolds, D. S., 1933, The composition and distribution of phosphate rock with special reference to the United States: U.S. Dept. Agriculture Tech. Bull. 364, 89 p.
- Jahns, R. H., 1944, Beryllium and tungsten deposits of the Iron Mountain district, Sierra and Socorro Counties, New Mexico, *with a section on The beryllium minerals*, by J. J. Glass: U.S. Geol. Survey Bull. 945-C, p. 45-79.
- Jewell, W. B., 1947, Barite, fluorite, galena, and sphalerite veins of Middle Tennessee: Tennessee Div. Geology Bull. 51, 114 p.
- Johnson, R. B., 1957, Goose Creek area, Pt. 1, of Refraction seismic investigations, Rosiclare fluorspar district, Illinois: Illinois Geol. Survey Circ. 231, 15 p.
- Johnston, W. D., Jr., 1928, Fluorspar in New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 4, 128 p.
- Jolly, J. L., and Heyl, A. V., 1964, Mineral paragenesis and zoning in the central Kentucky mineral district: *Econ. Geology*, v. 59, no. 4, p. 596-624.
- 1968, Mercury and other trace elements in sphalerite and wall-rocks from central Kentucky, Tennessee, and Appalachian zinc districts: U.S. Geol. Survey Bull. 1252-F, 29 p.
- Kazakov, A. V., and Sokolova, E. I., 1950, Usleviya obrazovaniya flyorita v osadochnykh porodakh (flyooritovaya sistema) [Conditions of the formation of fluorite in sedimentary rocks (The fluorite system)]: *Akad. Nauk SSSR Geol. Inst. Trudy*, no. 114, Geol. Ser. 40, p. 22-64; unpub. English translation in U.S. Geol. Survey TEI-386, 76 p., 1951.
- Keighin, C. W., 1968, Geochemical exploration in the southern Illinois fluorspar district—A progress report [abs.]: *Mining Eng.*, v. 20, no. 8, p. 25.
- Kelly, W. C., and Goddard, E. N., 1969, Telluride ores of Boulder County, Colorado: *Geol. Soc. America Mem.* 109, 237 p.
- Kesler, S. E., Van Loon, J. C., and Moore, C. M., 1973, Evaluation of ore potential of granodioritic rocks using water-extractable chloride and fluoride: *Canadian Mining and Metall. Bull.*, v. 66, no. 730, p. 56-60.
- King, P. B., compiler, 1967, National Atlas—Sheets 69-70, Tectonic features: U.S. Geol. Survey, scale 1:7,500,000.
- Koenig, J. B., 1956, The petrography of certain igneous dikes of Kentucky: *Kentucky Geol. Survey Bull.* 21, ser. 9, 57 p.
- Konovalov, G. S., 1959, Removal of microelements by the principal rivers of the USSR [in Russian]: *Akad. Nauk SSSR Doklady*, v. 129, no. 4, p. 912-915; English translation in *Acad. Sci. USSR Doklady*, *Earth Sci. Sec.*, v. 129, nos. 1-6, p. 1034-1037, 1960.
- Koritnig, S., 1972, Fluorine, in Wedepohl, K. H., ed., *Handbook of geochemistry*, v. II/3: Springer-Verlag, Berlin.
- Laurence, R. A., 1939, Origin of the Sweetwater, Tennessee, barite deposits: *Econ. Geology*, v. 34, no. 2, p. 190-200.
- 1960, Geologic problems in the Sweetwater barite district, Tennessee (Bradley Volume): *Am. Jour. Sci.*, v. 258-A, p. 170-179.
- Lee, D. E., and Van Loenen, R. E., 1970, Biotites from hybrid granitoid rocks of the southern Snake Range, Nevada, in *Geological Survey research 1970*: U.S. Geol. Survey Prof. Paper 700-D, p. D196-D206.
- 1971, Hybrid granitoid rocks of the southern Snake Range, Nevada: U.S. Geol. Survey Prof. paper 668, 48 p.
- Leonard, B. F., and Buddington, A. F., 1964, Ore deposits of the St. Lawrence County magnetite district, northwest Adirondacks, New York: U.S. Geol. Survey Prof. Paper 377, 259 p.
- Lindgren, Waldemar, 1933a, *Mineral deposits* [4th ed.]: New York and London, McGraw-Hill, 930 p.
- 1933b, Differentiation and ore deposition, Cordilleran region of the United States, in *Ore deposits of the Western States* (Lindgren volume): New York, Am. Inst. Mining Metall. Engineers, p. 152-180.
- Lindgren, Waldemar, and Ransome, F. L., 1906, Geology and gold deposits of the Cripple Creek district, Colorado: U.S. Geol. Survey Prof. Paper 54, 516 p.
- Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1972, Early and Middle Cenozoic [Pt.] 1 of Cenozoic volcanism and plate-tectonic evolution of the Western United States: *Royal Soc. London Philos. Trans.*, ser. A, v. 271, no. 1213, p. 217-248.
- Livingstone, D. A., 1963, Chemical composition of rivers and lakes, Chap. G of Fleischer, Michael, ed., *Data of geochemistry* [6th ed.]: U.S. Geol. Survey Prof. Paper 440-G, 64 p.
- Lovering, T. S., 1957, Halogen-acid alteration of ash at Fumarole No. 1, Valley of Ten Thousand Smokes, Alaska: *Geol. Soc. America Bull.*, v. 68, no. 12, pt. 1, p. 1585-1604.
- Lovering, T. S., and Goddard, E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geol. Survey Prof. Paper 223, 319 p.
- Luttrell, G. W., 1966, Base- and precious-metal and related ore deposits of Virginia: Virginia Div. Mineral Resources, *Mineral Resources Rept.* 7, 167 p.
- McAnulty, W. N., Sr., 1967, Fluorspar in Brewster County, Texas: *Texas Univ. Bur. Econ. Geology Geol. Circ.* 67-2, 16 p.
- McAnulty, W. N., and Levinson, A. A., 1964, Rare alkali and beryllium mineralization in volcanic tuffs, Honey Comb Hills, Juab County, Utah: *Econ. Geology*, v. 59, no. 5, p. 768-774.
- McAnulty, W. N., Sewell, C. R., Atkinson, D. R., and Rasberry, J. M., 1963, Aguachile beryllium-bearing fluorspar district, Coahuila, Mexico: *Geol. Soc. America Bull.*, v. 74, no. 6, p. 735-743.
- McGinnis, L. D., 1963, Earthquakes and crustal movement as related to water load in the Mississippi Valley region: *Illinois Geol. Survey Circ.* 344, 20 p.
- McGinnis, L. D., and Bradbury, J. C., 1964, Aeromagnetic study of the Hardin County area, Illinois: *Illinois Geol. Survey Circ.* 363, 12 p.
- McKelvey, V. E., Cathcart, J. B., Altschuler, Z. S., Swanson, R. W., and Buck, K. L., 1953, Domestic phosphate deposits, Chap. 11, in Pierre, W. H., and Norman, A. G., eds., *Soil and fertilizer phosphorus in crop nutrition*: New York, Academic Press, Inc., p. 347-376.
- McKeown, F. A., and Klemic, Harry, 1956, Rare-earth-bearing apatite at Mineville, Essex County, New York: U.S. Geol. Survey Bull. 1046-B, p. 9-23.
- MacMillan, R. T., 1970, Fluorine, in *Mineral facts and problems, 1970*: U.S. Bur. Mines Bull. 650, p. 989-1000.
- Maher, S. W., 1970, Barite resources of Tennessee: *Tennessee Div. Geology Rept. Inv.* 28, 40 p.
- Matson, E. J., and Trengove, R. R., 1957, Investigation of fluorspar deposit, Kaiser mine, Mineral County, Nevada: U.S. Bur. Mines Rept. Inv. 5344, 38 p.
- Miller, R. N., 1959, Geology of the South Moccasin Mountains, Fergus County, Montana: *Montana Bur. Mines and Geology Mem.* 37, 44 p.
- Miller, T. P., 1971, Petrology of the plutonic rocks of west-central Alaska: U.S. Geol. Survey open-file report, 136 p.
- Milner, H. B., 1962, Principles and applications, V. 2 of *Sedimentary petrography* [4th ed.]: New York, Macmillan Co., 715 p.
- Moore, J. G., 1959, The quartz diorite boundary line in the western United States: *Jour. Geology*, v. 67, no. 2, p. 198-210.
- 1962, K/Na ratio of Cenozoic igneous rocks of the western United States: *Geochim. et Cosmochim. Acta*, v. 26, p. 101-130.

- Morrill, Philip, 1951, New Hampshire mine and mineral localities: Dartmouth College Museum, 46 p.
- Mudd, H. T., 1949, Fluorspar and cryolite, in *Industrial minerals and rocks (nonmetallics other than fuels)* [2d ed.]: New York, Am. Inst. Mining Metall. Engineers, p. 381-403.
- Muir, N. M., 1947, Daisy fluorite mine, Rosiclare Lead & Fluorspar Mining Co., Hardin County, Illinois: U.S. Bur. Mines Rept. Inv. 4075, 16 p.
- Nackowski, M. P., 1957, Geochemical prospecting applied to the Illinois-Kentucky fluorspar area, in Erikson, J. E., *Geochemical prospecting abstracts, July 1952-December 1954*: U.S. Geol. Survey Bull. 1000-G, p. 378.
- National Materials Advisory Board, 1970, Trends in the usage of fluorspar: Washington, D. C., Natl. Research Council, NMAB-269, 71 p.
- Noble, D. C., Smith, V. C., and Peck, L. C., 1967, Loss of halogens from crystallized and glassy silicic volcanic rocks: *Geochim. et Cosmochim. Acta*, v. 31, no. 2, p. 215-223.
- Norton, J. J., 1970, Composition of a pegmatite, Keystone, South Dakota: *Am. Mineralogist*, v. 55, nos. 5-6, p. 981-1002.
- Norton, J. J., Page, L. R., and Brobst, D. A., 1962, Geology of the Hugo pegmatite, Keystone, South Dakota: U.S. Geol. Survey Prof. Paper 297-B, p. 49-127.
- Norwood, J. G., 1866, Report on the Rosiclare lead mines, in Hardin County [Illinois], Chap. 13 of Worthen, A. H., Whitney, J. D., Lesquereux, Leo, and Englemann, Henry. *Geology: Illinois Geol. Survey*, v. 1, p. 366-372.
- Oesterling, W. A., 1952, Geologic and economic significance of the Hutson zinc mine, Salem, Kentucky—its relation to the Illinois-Kentucky fluorspar district: *Econ. Geology*, v. 47, no. 3, p. 316-338.
- Olson, J. C., Shawe, D. R., Pray, L. C., and Sharp, W. N., 1954, Rare-earth mineral deposits of the Mountain Pass district, San Bernardino County, California, with a foreword on History of the discovery at Mountain Pass, California, by D. F. Hewett: U.S. Geol. Survey Prof. Paper 261, 75 p. [1955].
- Olson, N. K., compiler and ed., 1966, Geology of the Miocene and Pliocene series in the north Florida-south Georgia area—Atlantic Coastal Plain Geol. Assoc., 7th, and Southeastern Geol. Soc., 12th Ann. Field Conf., 1966: 94 p.
- O'Neill, J. F., 1950, Investigation of Gilley fluorspar deposits, Cherokee County, Alabama: U.S. Bur. Mines Rept. Inv. 4660, 6 p.
- Oriel, S. S., 1950, Geology and mineral resources of the Hot Springs window, Madison County, North Carolina: North Carolina Div. Mineral Resources Bull. 60, 70 p.
- Osterwald, F. W., Osterwald, D. B., Long, J. S., Jr., and Wilson, W. H., 1959, Mineral resources of Wyoming: Wyoming Geol. Survey Bull. 50, 259 p.
- Paige, Sidney, 1911, Mineral resources of the Llano-Burnet region, Texas, with an account of the pre-Cambrian geology: U.S. Geol. Survey Bull. 450, 103 p.
- Pakiser, L. C., and Zietz, Isidore, 1965, Transcontinental Crustal and upper-mantle structure: *Rev. Geophysics*, v. 3, no. 4, p. 505-520.
- Paley, W. S., chm., 1952, Fluorspar, Chap. 18, in *The outlook for key commodities, V. 2 of Resources for freedom*: [U.S.] President's Materials Policy Comm., p. 88-91 (Washington, U.S. Govt. Printing Office).
- Panov, B. S., 1962, Fluorite in carbonates at the southwestern margin of the Donets basin [in Russian]: *Akad. Nauk SSSR Doklady*, v. 147, no. 5, p. 1172-1174; English translation in *Acad. Sci. USSR Doklady, Earth Sci. Sec.*, v. 147, nos. 1-6 p. 160-164, 1964.
- Pardee, J. T., 1918, Geology and mineral deposits of the Colville Indian Reservation, Washington: U.S. Geol. Survey Bull. 677, 186 p.
- Pardee, J. T., and Park, C. F., Jr., 1948, Gold deposits of the Southern Piedmont: U.S. Geol. Survey Prof. Paper 213, 156 p.
- Park, W. C., and Amstutz, G. C., 1968, Primary "cut and fill" channels and gravitational diagenetic features: *Mineralium Deposita*, v. 3, p. 66-80.
- Parker, J. M., 3d, 1963, Geologic setting of the Hamme tungsten district, North Carolina and Virginia: U.S. Geol. Survey Bull. 1122-G, 69 p.
- Parker, R. L., and Havens, R. G., 1963, Thortveitite associated with fluorite, Ravalli County, Montana, in *Short papers in geology and hydrology*: U.S. Geol. Survey Prof. Paper 475-B, p. B10-B11.
- Patton, W. W., Jr., and Matzko, J. J., 1959, Phosphate deposits in northern Alaska: U.S. Geol. Survey Prof. Paper 302-A, p. 1-17.
- Perhac, R. M., and Heinrich, E. W., 1964, Fluorite-bastnaesite deposits of the Gallinas Mountains, New Mexico, and bastnaesite paragenesis: *Econ. Geology*, v. 59, no. 2, p. 226-239.
- Perrét, F. A., 1924, The Vesuvius eruption of 1906—study of a volcanic cycle: Carnegie Inst. Washington Pub. 339, 151 p.
- Peters, W. C., 1958, Geologic characteristics of fluorspar deposits in the western United States: *Econ. Geology*, v. 53, no. 6, p. 663-688.
- Pinckney, D. M., and Rye, R. O., 1972, Variation of O_{18}/O_{16} , C_{13}/C_{12} , texture, and mineralogy in altered limestone in the Hill mine, Cave-in-Rock district, Illinois: *Econ. Geology*, v. 67, no. 1, p. 1-18.
- Quinn, A. W., 1971, Bedrock geology of Rhode Island: U.S. Geol. Survey Bull. 1295, 68 p.
- Ratté, J. C., Landis, E. R., Gaskill, D. L., and Raabe, R. G., 1969, Mineral resources of the Blue Range primitive area, Greenlee County, Arizona, and Catron County, New Mexico, with a section on Aeromagnetic interpretation, by G. P. Eaton: U.S. Geol. Survey Bull. 1261-E, 91 p.
- Ratté, J. C., and Steven, T. A., 1967, Ash flows and related volcanic rocks associated with the Creede caldera, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 524-H, 58 p.
- Reeves, R. G., and Kral, V. E., 1955, Geology and iron ore deposits of the Buena Vista Hills, Churchill and Pershing Counties, Nevada, Pt. A, in *Iron ore deposits of Nevada*: Nevada Bur. Mines Bull. 53, p. 1-32.
- Reid, R. R., 1963, Reconnaissance geology of the Sawtooth Range: Idaho Bur. Mines and Geology Pamph. 129, 37 p.
- Rhoades, R. F., and Mistler, A. J., 1941, Post-Appalachian faulting in western Kentucky: *Am. Assoc. Petroleum Geologists Bull.*, v. 25, no. 11, p. 2046-2056.
- Roberts, W. L., and Rapp, George, Jr., 1965, Mineralogy of the Black Hills: South Dakota School Mines and Technology Bull. 18, 268 p.
- Robinson, L. C., 1931, Vein deposits of central Kentucky: Kentucky Geol. Survey, ser. 6, v. 41, p. 3-127.
- Rogers, W. B., and Hays, W. H., 1967, Geologic map of the Fredonia quadrangle, western Kentucky: U.S. Geol. Survey Geol. Quad. Map GQ-607.
- Ross, C. A., 1963, Structural framework of southernmost Illinois: Illinois Geol. Survey Circ. 351, 27 p.
- Ross, C. P., 1950, Fluorspar prospects of Montana: U.S. Geol. Survey Bull. 955-E, p. 173-224.
- Ross, D. C., 1961, Geology and mineral deposits of Mineral County, Nevada: Nevada Bur. Mines Bull. 58, 98 p.
- Rothrock, H. E., Johnson, C. H., and Hahn, A. D., 1946, Fluorspar resources of New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 21, 239 p.
- Ruch, R. R., 1968, Neutron activation analysis at the Illinois State Geological Survey: Illinois Geol. Survey Indus. Minerals Note 34, 8 p.
- Russel, R. T., [no date, 1947?], The Poncha fluorspar deposits, Chaffee County, Colorado: U.S. Geol. Survey Strategic Minerals Inv. Prelim. Rept. 3-210, 12 p.
- 1950, The geology of the Poncha fluorspar district, Chaffee County, Colorado: Univ. Cincinnati unpub. Ph. D. thesis, 70 p.
- Sahinen, U. M., 1962, Fluorspar deposits in Montana: Montana Bur. Mines and Geology Bull. 28, 38 p.
- Sainsbury, C. L., 1964a, Association of beryllium with tin deposits rich in fluorite: *Econ. Geology*, v. 59, no. 5, p. 920-926.

- 1964b, Geology of Lost River mine area, Alaska: U.S. Geol. Survey Bull. 1129, 80 p.
- 1965, Planetable maps and drill logs of fluorite and beryllium deposits, Lost River area, Alaska: U.S. Geol. Survey open-file report, 38 p.
- 1969, Geology and ore deposits of the central York Mountains, western Seward Peninsula, Alaska: U.S. Geol. Survey Bull. 1287, 101 p. [1970].
- Sainsbury, C. L., and Kleinhampl, F. J., 1969, Fluorite deposits of the Quinn Canyon Range, Nevada: U.S. Geol. Survey Bull. 1272-C, 22 p. [1970].
- Sang Kyu Yun, Hyo Joon Seo, Sahng Yup Kim, Jae Sand Cho, and Nam Iue Hong, 1970, Detailed geochemical exploration for Mo-W and CaF₂ in Hwanggangri region, Republic of Korea, in Second seminar on methods and techniques of geochemical exploration in the humid tropical environment, Peradeniya, Ceylon: Document GSM (2)/107, 9 p.
- Sever, C. W., Cathcart, J. B., and Patterson, S. H., 1967, Phosphate deposits of south-central Georgia and north-central peninsular Florida: Georgia Dept. Mines, Mining and Geology, South Georgia Minerals Program, Proj. Rept. 7, 62 p.
- Shawe, D. R., 1961, Rhyolites in the Egan range south of Ely, Nevada, in short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424-B, p. B178-B181.
- 1965, Strike-slip control of Basin-Range structure indicated by historical faults in western Nevada: Geol. Soc. America Bull., v. 76, no. 12, p. 1361-1373.
- 1966, Arizona-New Mexico and Nevada-Utah beryllium belts, in Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550-C, p. C206-C213.
- 1968, Geology of the Spor Mountain beryllium district, Utah, in Ridge, J. D., ed., Ore deposits of the United States 1933-1967, (Graton-Sales Volume), V. 2: New York, Am. Inst. Mining Metall. and Petroleum Engineers, p. 1148-1161.
- 1972, Reconnaissance geology and mineral potential of Thomas, Keg, and Desert calderas, central Juab County, Utah, in Geological Survey research 1972: U.S. Geol. Survey Prof. Paper 800-B, p. B67-B77.
- Shawe, D. R., and Bernold, Stanley, 1966, Beryllium content of volcanic rocks: U.S. Geol. Survey Bull. 1214-C, 11 p.
- Shawe, F. R., Reeves, R. G., and Kral, V. E., 1962, Iron ore deposits of northern Nevada, Pt. C, in Iron ore deposits of Nevada: Nevada Bur. Mines Bull. 53, p. 79-1300.
- Sheldon, R. P., 1963, Physical stratigraphy and mineral resources of Permian rocks in western Wyoming: U.S. Geol. Survey Prof. Paper 313-B, p. 49-273.
- Shenon, P. J., and Ross, C. P., 1936, Geology and ore deposits near Edwardsburg and Thunder Mountain, Idaho: Idaho Bur. Mines and Geology Pamph. 44, 45 p.
- Sheppard, R. A., and Gude, A. J., 3d, 1969, Authigenic fluorite in Pliocene lacustrine rocks near Rome, Malheur County, Oregon, in Geological Survey research 1969: U.S. Geol. Survey Prof. Paper 650-D, p. D69-D74 [1970].
- Sheridan, D. M., Stephens, H. G., Staatz, M. H., and Norton, J. J., 1957, Geology and beryl deposits of the Peerless pegmatite, Pennington County, South Dakota: U.S. Geol. Survey Prof. Paper 297-A, p. 1-47.
- Sheridan, D. M., Taylor, R. B., and Marsh, S. P., 1968, Rutile and topaz in Precambrian gneiss, Jefferson and Clear Creek Counties, Colorado: U.S. Geol. Survey Circ. 567, 7 p.
- Siems, H. B., 1951, Fertilizers, in Kirk, R. E., and Othmer, D. F., eds., Encyclopedia of chemical technology: New York, Interscience Encyclopedia, v. 6, p. 376-452.
- Silliman, Benjamin, 1821, Virginia and Illinois fluorspar: Am. Jour. Sci., [1st ser.], v. 3, p. 243-245.
- Simons, F. S., 1964, Geology of the Klondyke quadrangle, Graham and Pinal Counties, Arizona: U.S. Geol. Survey Prof. Paper 461, 173 p.
- Snyder, F. G., and Gerdemann, P. E., 1965, Explosive igneous activity along an Illinois-Missouri-Kansas axis: Am. Jour. Sci., v. 263, no. 6, p. 465-493.
- Spada, Aldo, 1969, Il giacimento di fluorite e baritina esalativo-sedimentario in "facies" lacustre, intercalato nei sedimenti piroclastici della zona di Castel Giuliano, in prov. di Roma [Lacustrine-facies exhalative-sedimentary fluorite and barite deposits interbedded in pyroclastic sediments of the Castel Giuliano area, Rome]: Industria Mineraria, v. 20, no. 10, p. 501, 504-510, 515-518.
- Staatz, M. H., 1963, Geology of the beryllium deposits in the Thomas Range, Juab County, Utah: U.S. Geol. Survey Bull. 1142-M, 36 p.
- Staatz, M. H., and Carr, W. J., 1964, Geology and mineral deposits of the Thomas and Dugway Ranges, Juab and Tooele Counties, Utah: U.S. Geol. Survey Prof. Paper 415, 188 p.
- Staatz, M. H., and Griffiths, W. R., 1961, Beryllium-bearing tuff in the Thomas Range, Juab County, Utah: Econ. Geology, v. 56, no. 5, p. 941-950.
- Staatz, M. H., and Osterwald, F. W., 1959, Geology of the Thomas Range fluorspar district, Juab County, Utah: U.S. Geol. Survey Bull. 1069, 97 p.
- Stefánsson, Kristinn, and Sigurjónsson, Júlíus, 1957, Temporary increase in fluorine content of water following the eruption, in Einarsson, T., Kjartansson, G., and Thorarinnsson, S., eds., The eruption of Hekla 1947-1948: Vísindafélag Íslendinga Rit, v. 3, no. 1/3, 13 p.
- Stenzel, H. B., 1932, Pre-Cambrian of the Llano uplift, Texas [abs.]: Geol. Soc. America Bull., v. 43, no. 1, p. 143-144.
- Steven, T. A., 1949, Geology and fluorspar deposits of the St. Peters Dome district, Colorado: Colorado Sci. Soc. Proc., v. 15, no. 6, p. 259-284.
- 1960, Geology and fluorspar deposits, Northgate district, Colorado: U.S. Geol. Survey Bull. 1082-F, p. 323-422 [1961].
- 1968, Geologic map of the Wagon Wheel Gap fluorspar district, Colorado: U.S. Geol. Survey open-file map, 1:20,000.
- Steven, T. A., and Ratté, J. C., 1960, Geology and ore deposits of the Summitville district, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 343, 70 p.
- Stuckey, J. L., 1942, Barite deposits in North Carolina, in Newhouse, W. H., ed., Ore deposits as related to structural features: Princeton, N. J., Princeton Univ. Press, p. 106-108.
- Sutton, A. H., 1953, Fluorspar resources of the southeast, in McGrain, Preston, ed., Techniques of mineral resources exploration and evaluation—Southeastern Mineral Symposium, 1950, Proc.: Kentucky Geol. Survey, Spec. Pub. 1, Ser. 9, p. 139-149.
- 1954, Fluorspar supplies in the United States [abs.], in Annual meeting, 1954: Am. Inst. Mining, Metall. and Petroleum Engineers, Indus. Mining Div., p. 3-5.
- Swanson, V. E., and Vine, J. D., 1972, Composition of coal, Southwestern United States: Geol. Soc. America Abs. with Programs, v. 4, no. 7, p. 683-684.
- Sweeney, J. W., 1971, Phosphate rock: U.S. Bur. Mines Minerals Yearbook, 1969, v. 1-2, p. 907-920.
- Taber, J. W., 1952, Crystal Mountain fluorite deposits, Ravalli County, Montana: U.S. Bur. Mines Rept. Inv. 4916, 8 p.
- 1953, Montana's Crystal Mt. fluorite deposit is big and high grade: Mining World, v. 15, no. 7, p. 43-46.
- Temple, A. K., and Grogan, R. M., 1963, Manto deposits of fluorspar, northern Coahuila, Mexico: Econ. Geology, v. 58, no. 7, p. 1037-1053.
- Thompson, T. G., and Taylor, H. J., 1933, Determination and occurrence of fluorides in sea water: Indus. Eng. Chemistry, Anal. Ed., v. 5, no. 2, p. 87-89.

- Thorarinsson, Sigurdur, 1970, Hekla, a notorious volcano: Reykjavik Almenna Bókafélagid, 62 p.
- Thurston, W. R., 1946, Preliminary report on the Baxter fluor spar deposit near Broken Hills, Nevada: U.S. Geol. Survey Strategic Minerals Inv. Prelim. Rept. 3-196, 3 p.
- Thurston, W. R., and Hardin, G. C., Jr., 1954, Moore Hill fault system, Crittenden and Livingston Counties, in Fluorspar deposits in western Kentucky, Pt. 3: U.S. Geol. Survey Bull. 1012-E, p. 81-113.
- Thurston, W. R., Staatz, M. H., Cox, D. C., and others, 1954, Fluorspar deposits of Utah: U.S. Geol. Survey Bull. 1005, 53 p.
- Trace, R. D., 1947, The Fourth of July and Luckie No. 1 and No. 2 fluor spar veins, Greenlee County, Arizona: U.S. Geol. Survey Strategic Minerals Inv., Prelim. Rept. 3-207, 6 p.
- 1954, Mineral Ridge area, Livingston and Crittenden Counties, in Fluorspar deposits in western Kentucky, Pt. 2: U.S. Geol. Survey Bull. 1012-D, p. 59-79.
- 1960, Significance of unusual mineral occurrence at Hicks Dome, Hardin County, Illinois, in Short papers in the geological sciences: U.S. Geol. Survey Prof. Paper 400-B, p. B63-B64.
- 1962a, Geology of the Salem quadrangle, Kentucky: U.S. Geol. Survey Geol. Quad. Map GQ-206.
- 1962b, Geology and fluor spar deposits of the Levias-Keystone and Dike-Eaton areas, Crittenden County, Kentucky: U.S. Geol. Survey Bull. 1122-E, 26 p.
- 1966, Geologic map of the Marion quadrangle, Crittenden and Caldwell Counties, Kentucky: U.S. Geol. Survey Geol. Quad. Map GQ-547.
- Tweto, Ogden, Bryant, Bruce, and Williams, F. E., 1970, Mineral resources of the Gore Range-Eagles Nest Primitive Area and vicinity, Summit and Eagle Counties, Colorado: U.S. Geol. Survey Bull. 1319-C, 127 p.
- Ulrich, E. O., and Smith, W. S. T., 1905, The lead, zinc, and fluor spar deposits of western Kentucky: U.S. Geol. Survey Prof. Paper 36, 218 p.
- Underwood, J. R., Jr., 1963, Geologic map of Eagle Mountains and vicinity, Hudspeth County, Texas: Texas Univ. Bur. Econ. Geology Geol. Quad. Map 26, 32 p.
- U.S. Bureau of Mines, 1969, Minerals yearbook, 1968: U.S. Bur. Mines, v. 1-2, 1208 p.
- 1973, Minerals yearbook, 1971: U.S. Bur. Mines, v. 1, 1303 p.
- U.S. Geological Survey, 1956, Fluorspar reserves of the United States estimated: U.S. Geol. Survey Press Release, Nov. 23, 1956, 3 p.
- 1968, Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600-A, 371 p.
- 1970, Geological Survey research 1970: U.S. Geol. Survey Prof. Paper 700-A, 426 p. [1971].
- Valentine, G. M., 1949, Nonmetallic minerals, Pt. 1 of Inventory of Washington minerals: Washington Div. Mines and Geology Bull. 37, v. 1, text, 175 p., v. 2, maps, 83 p. (2d ed., 1960, revised by M. T. Huntting).
- Van Alstine, R. E., 1947, Fluorspar investigations, in Vanderwilt, J. W., [ed.], Mineral resources of Colorado: Denver, Colorado Mineral Resources Board, p. 457-465.
- 1954, Geologic features of the fluor spar deposits of the United States [abs.], in Annual meeting 1954: Am. Inst. Mining Metall. and Petroleum Engineers, Indus. Mining Div., p. 2-3.
- 1964, Fluorspar, in mineral and water resources of Colorado: U.S. 88th Cong., 2d sess., Senate Comm. Interior and Insular Affairs, Comm. Print, p. 160-165.
- 1965, Geochemical prospecting in the Browns Canyon fluor spar district, Chaffee County, Colorado, in Geological Survey research 1965: U.S. Geol. Survey Prof. Paper 525-D, p. D59-D64.
- 1966, Fluorspar, in Mineral and water resources of Washington: U.S. 89th Cong., 2d sess., Senate Comm. Interior and Insular Affairs, Comm. Print, p. 199-204.
- 1969, Geology and mineral deposits of the Poncha Springs NE quadrangle, Chaffee County, Colorado, with a section on Fluorspar mines and prospects, by R. E. Van Alstine and D. C. Cox: U.S. Geol. Survey Prof. Paper 626, 52 p. [1970].
- Van Alstine, R. E., Estrada, Samuel, de la Garza, Ernesto, 1962, Investigacion de los principales distritos de fluorita en Mexico: Mexico Consejo Recursos Nat. no Renovables Bol. 62, 62 p.
- Van Alstine, R. E., and Moore, R. T., 1969, Fluorspar, in Mineral and water resources of Arizona: U.S. 90th Cong., 2d sess., Senate Comm. Interior and Insular Affairs, Comm. Print, p. 348-357.
- Van Alstine, R. E., and Sweeney, J. W., 1968, Fluorspar, in Mineral resources of the Appalachian Region: U.S. Geol. Survey Prof. Paper 580, p. 286-289.
- Wallace, S. R., Muncaster, N. K., Jonson, D. C., MacKenzie, W. B., Bookstrom, A. A., and Surface, V. E., 1968, Multiple intrusion and mineralization at Climax, Colorado, in Ridge, J. D., ed., Ore deposits of the United States, 1933-1967 (Graton Sales Volume), V. 1: New York, Am. Inst. Mining Metall. and Petroleum Engineers, p. 605-640.
- Warne, J. D., 1947, Northgate fluor spar, Jackson County, Colorado: U.S. Bur. Mines Rept. Inv. 4106, 23 p.
- Warner, L. A., Holser, W. T., Wilmarth, V. R., and Cameron, E. N., 1959, Occurrence of nonpegmatite beryllium in the United States: U.S. Geol. Survey Prof. Paper 318, 198 p.
- Weaver, C. E., 1912, Geology and ore deposits of the Index mining district: Washington Geol. Survey Bull. 7, 96 p.
- Weis, P. L., Armstrong, F. C., and Rosenblum, Samuel, 1958, Reconnaissance for radioactive minerals in Washington, Idaho, and western Montana 1952-1955: U.S. Geol. Survey Bull. 1074-B, p. 7-48 [1959].
- Weis, P. L., Schmitt, L. J., Jr., and Tucheck, E. T., 1972, Mineral resources of the Salmon River Breaks Primitive Area, Idaho, with a section on Aeromagnetic survey, by W. E. Davis: U.S. Geol. Survey Bull. 1353-C, 91 p.
- Weller, J. M., Grogan, R. M., and Tippie, F. E., 1952, Geology of the fluor spar deposits of Illinois: Illinois Geol. Survey Bull. 76, 147 p.
- Weller, Stuart, and Sutton, A. H., 1951, Geologic map of the western Kentucky fluor spar district: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-2.
- White, D. E., Hem, J. D., and Waring, G. A., 1963, Chemical composition of subsurface waters, Chap. F of Fleischer, Michael, ed., Data of geochemistry [6th ed.]: U.S. Geol. Survey Prof. Paper 440-F, 67 p.
- White, D. E., Thompson, G. A., and Sandberg, C. H., 1964, Rocks, structure, and geologic history of Steamboat Springs thermal area, Washoe County, Nevada: U.S. Geol. Survey Prof. Paper 458-B, 63 p.
- White, D. E., and Waring, G. A., 1963, Volcanic emanations, Chap. K of Fleischer, Michael, ed., Data of geochemistry [6th ed.]: U.S. Geol. Survey Prof. Paper 440-K, 29 p.
- White, W. H., and MacKenzie, W. B., 1973, Hydrothermal alteration associated with the Henderson molybdenite deposit [Colorado] [abs.]: Econ. Geology, v. 68, no. 1, p. 142.
- Williams, F. E., 1966, Fluorspar deposits of New Mexico: U.S. Bur. Mines Inf. Circ. 8307, 143 p.
- Williamson, D. R., 1961, Mexican fluorite deposits: Colorado School Mines Mineral Industries Bull., v. 4, no. 2, 15 p.
- Wilmarth, V. R., Bauer, H. L., Jr., Staatz, M. H., and Wyant, D. G., 1952, Uranium in fluorite deposits, in Selected papers on uranium deposits in the United States: U.S. Geol. Survey Circ. 220, p. 13-18.
- Wilson, E. D., 1933, Geology and mineral deposits of southern Yuma County, Arizona: Arizona Bur. Mines Bull. 134, Geol. Ser. 7, v. 4, no. 2, 236 p.

- 1950, Fluorspar in Arizona: Arizona Bur. Mines Circ. 15, 13 p.
- 1951, Castle Dome district, Chap. 10, *in* Arizona lead and zinc deposits, Pt. 2: Arizona Bur. Mines Bull. 158, Geol. Ser. 19, v. 22, no. 3, p. 98-115.
- Woollard, G. P., 1968, The interrelationship of the crust, the upper mantle, and isostatic gravity anomalies in the United States, *in* The crust and upper mantle of the Pacific area—Internat. Upper Mantle Proj., Sci. Rept. 15: Am. Geophys. Union Geophys. Mon. 12 (Natl. Acad. Sci.-Natl. Research Council Pub. 1687), p. 312-341.
- 1969, Tectonic activity in North America as indicated by earthquakes, *in* The Earth's crust and upper mantle—structure, dynamic processes, and their relation to deep-seated geological phenomena: Am. Geophys. Union Geophys. Mon. 13 (Natl. Acad. Sci.-Natl. Research Council Pub. 1708), p. 125-133.
- Woollard, G. P., chm., and Joesting, H. R., coordinator, 1964, Bouguer gravity anomaly map of the United States (exclusive of Alaska and Hawaii): Am. Geophys. Union and U.S. Geol. Survey.
- Worl, R. G., Van Alstine, R. E., and Heyl, A. V., 1974, compilers, Fluorite in the United States (exclusive of Hawaii): U.S. Geol. Survey Mineral Inv. Resource Map MR-60.
- Worl, R. G., Van Alstine, R. E., and Shawe, D. R., 1973, Fluorine, *in* Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geol. Survey Prof. Paper 820, p. 223-235.
- Wright, T. L., 1971, Chemistry of Kilauea and Mauna Loa lava in space and time: U.S. Geol. Survey Prof. Paper 735, 40 p. [1972].
- Wright, T. L., and Fiske, R. S., 1971, Origin of the differentiated and hybrid lavas of Kilauea volcano, Hawaii: Jour. Petrology, v. 12, no. 1, p. 1-65.
- Yates, R. G., and Thompson, G. A., 1959, Geology and quicksilver deposits of the Terlingua district, Texas: U.S. Geol. Survey Prof. Paper 312, 114 p.
- Zartman, R. E., Brock, M. R., Heyl, A. V., and Thomas, H. H., 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States: Am. Jour. Sci., v. 265, no. 10, p. 848-870.
- Zies, E. G., 1929, The fumarolic incrustations and their bearing on ore deposition, Pt. 1; *and* The acid gases contributed to the sea during volcanic activity, Pt. 2, *in* The Valley of Ten Thousand Smokes; Natl. Geog. Soc., Contributed Tech. Papers, Katmai Ser., v. 1, no. 4, 79 p.
- Zietz, Isidore, Andreasen, G. E., and Cain, J. C., 1970, Magnetic anomalies from satellite magnetometer: Jour. Geophys. Research, v. 75, no. 20, p. 4007-4015.
- Zietz, Isidore, and Kirby, J. R., Jr., 1972, Aeromagnetic map of Colorado: U.S. Geol. Survey Geophys. Inv. Map GP-836.

