

Shorter Contributions to Stratigraphy and Structural Geology, 1979

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CONVERSION FACTORS

Metric unit	Inch-Pound equivalent	Metric unit	Inch-Pound equivalent
Length		Specific combinations—Continued	
millimeter (mm)	= 0.03937 inch (in)	liter per second (L/s)	= .0353 cubic foot per second
meter (m)	= 3.28 feet (ft)	cubic meter per second per square kilometer [(m ³ /s)/km ²]	= 91.47 cubic feet per second per square mile [(ft ³ /s)/mi ²]
kilometer (km)	= .62 mile (mi)	meter per day (m/d)	= 3.28 feet per day (hydraulic conductivity) (ft/d)
Area		meter per kilometer (m/km)	= 5.28 feet per mile (ft/mi)
square meter (m ²)	= 10.76 square feet (ft ²)	kilometer per hour (km/h)	= .9113 foot per second (ft/s)
square kilometer (km ²)	= .386 square mile (mi ²)	meter per second (m/s)	= 3.28 feet per second
hectare (ha)	= 2.47 acres	meter squared per day (m ² /d)	= 10.764 feet squared per day (ft ² /d) (transmissivity)
Volume		cubic meter per second (m ³ /s)	= 22.826 million gallons per day (Mgal/d)
cubic centimeter (cm ³)	= 0.061 cubic inch (in ³)	cubic meter per minute (m ³ /min)	= 264.2 gallons per minute (gal/min)
liter (L)	= 61.03 cubic inches	liter per second (L/s)	= 15.85 gallons per minute
cubic meter (m ³)	= 35.31 cubic feet (ft ³)	liter per second per meter [(L/s)/m]	= 4.83 gallons per minute per foot [(gal/min)/ft]
cubic meter	= .00081 acre-foot (acre-ft)	kilometer per hour (km/h)	= .62 mile per hour (mi/h)
cubic hectometer (hm ³)	= 810.7 acre-feet	meter per second (m/s)	= 2.237 miles per hour
liter	= 2.113 pints (pt)	gram per cubic centimeter (g/cm ³)	= 62.43 pounds per cubic foot (lb/ft ³)
liter	= 1.06 quarts (qt)	gram per square centimeter (g/cm ²)	= 2.048 pounds per square foot (lb/ft ²)
liter	= .26 gallon (gal)	gram per square centimeter	= .0142 pound per square inch (lb/in ²)
cubic meter	= .00026 million gallons (Mgal or 10 ⁶ gal)	Temperature	
cubic meter	= 6.290 barrels (bbl) (1 bbl= 42 gal)	degree Celsius (°C)	= 1.8 degrees Fahrenheit (°F)
Weight		degrees Celsius (temperature)	= [(1.8 × °C) + 32] degrees Fahrenheit
gram (g)	= 0.035 ounce, avoirdupois (oz avdp)		
gram	= .0022 pound, avoirdupois (lb avdp)		
metric tons (t)	= 1.102 tons, short (2,000 lb)		
metric tons	= 0.9842 ton, long (2,240 lb)		
Specific combinations			
kilogram per square centimeter (kg/cm ²)	= 0.96 atmosphere (atm)		
kilogram per square centimeter	= .98 bar (0.9869 atm)		
cubic meter per second (m ³ /s)	= 35.3 cubic feet per second (ft ³ /s)		

Paleogene Sedimentary and Volcanogenic Rocks from Adak Island, Central Aleutian Islands, Alaska

By JAMES R. HEIN *and* HUGH McLEAN

SHORTER CONTRIBUTIONS TO STRATIGRAPHY AND
STRUCTURAL GEOLOGY, 1979

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1126-E



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PALEOGENE SEDIMENTARY AND VOLCANOGENIC ROCKS FROM ADAK ISLAND, CENTRAL ALEUTIAN ISLANDS, ALASKA

By JAMES R. HEIN and HUGH MCLEAN

ABSTRACT

The Andrew Lake Formation on northern Adak Island, here redefined, consists of conglomerate, sandstone, chert, shale, and pyroclastic ejecta of late Eocene age. These strata were deposited in a marine basin no deeper than 500 meters. Nonmarine to shallow marine volcanoclastic rocks, probably correlative in age with the Andrew Lake Formation, crop out in the Wedge Point area of southwestern Adak Island. The sedimentary rocks contain secondary minerals including chlorite, vermiculite, smectite, analcime, laumontite, clinoptilolite, wairakite, and the rare zeolite yugawaralite. These minerals reflect a complex history of alteration involving burial diagenesis, migration of hydrothermal solutions associated with intrusion of granodiorite plutons, and local thermal metamorphism caused by intrusion of dikes and sills. The late Eocene strata both at Andrew Lake and near Wedge Point overlie the Finger Bay Volcanics, which consists of highly altered interbedded flows and pyroclastic rocks that contain secondary minerals (chlorite, albite, actinolite, muscovite, epidote) characteristic of greenschist-facies metamorphism. The age of the Finger Bay Volcanics is unknown, but because of the contrast in degree of alteration and metamorphism between it and the overlying Andrew Lake Formation, it is believed to be late Paleocene or early Eocene. The late Eocene strata are low in total organic carbon and are therefore not considered a potential source rock for petroleum.

Other workers suggest that subduction of the Kula ridge spreading center beneath the Aleutian arc, 30 million years ago, resulted in an episode of regional greenschist-facies metamorphism throughout the arc. However, absence of metamorphism in the Andrew Lake Formation indicates either that the Kula ridge was subducted at an earlier time (about 50 m.y. ago) or that low-grade regional metamorphism did not accompany the subduction of the spreading center.

INTRODUCTION

Adak Island, part of the Andreanof group of central Aleutian Islands, consists of late Cenozoic strato-volcanoes that overlie uplifted Tertiary volcanic, sedimentary, and plutonic rocks (fig. 1). In general, most of the larger Aleutian islands are characterized by a Late Cretaceous(?) and early Tertiary mafic

volcanic basement overlain by Paleocene volcanic and sedimentary rocks. Commonly, as on Adak Island, lower Tertiary rocks of the Aleutians are intruded by middle Miocene plutonic bodies, mostly granodiorite (Fraser and Snyder, 1959; Marlow and others, 1973; DeLong and others, 1978).

Marine volcanoclastic strata that crop out between Andrew Lake and Clam Lagoon on northern Adak Island (figs. 1 and 2) were mapped by Coats (1956) as part of the Finger Bay Volcanics and were tentatively dated as Paleozoic on the basis of leaflike impressions identified as *Annularia stellata*. Because rocks of unequivocal Paleozoic age were not known from other Aleutian islands, Scholl, Green, and Marlow (1970) re-examined these strata and found that the "*Annularia*" beds are in fact of middle or late Eocene age on the basis of foraminifers, dinoflagellates, and pelecypods. They named the fossiliferous strata the Andrew Lake Formation and reported that it rests positionally on the Finger Bay Volcanics, which they assumed to be of slightly older Tertiary age.

The Finger Bay Volcanics, defined by Coats (1947), occurs widely on Adak Island and is especially well exposed on southern Adak (Fraser and Snyder, 1959). Fraser and Snyder (1959) found that, in general, the Finger Bay Volcanics consists of pervasively altered pyroclastic deposits and basaltic and andesitic flows. They deduced from dated rocks exposed on nearby Kanaga Island that the volcanic rocks of southern Adak are probably of Tertiary age. They also included bedded pyroclastic rocks, volcanic wacke, and argillite as part of the Finger Bay Volcanics. One of these sedimentary rocks sections is well exposed at Wedge Point on the Yakak Peninsula (figs. 1 and 3).

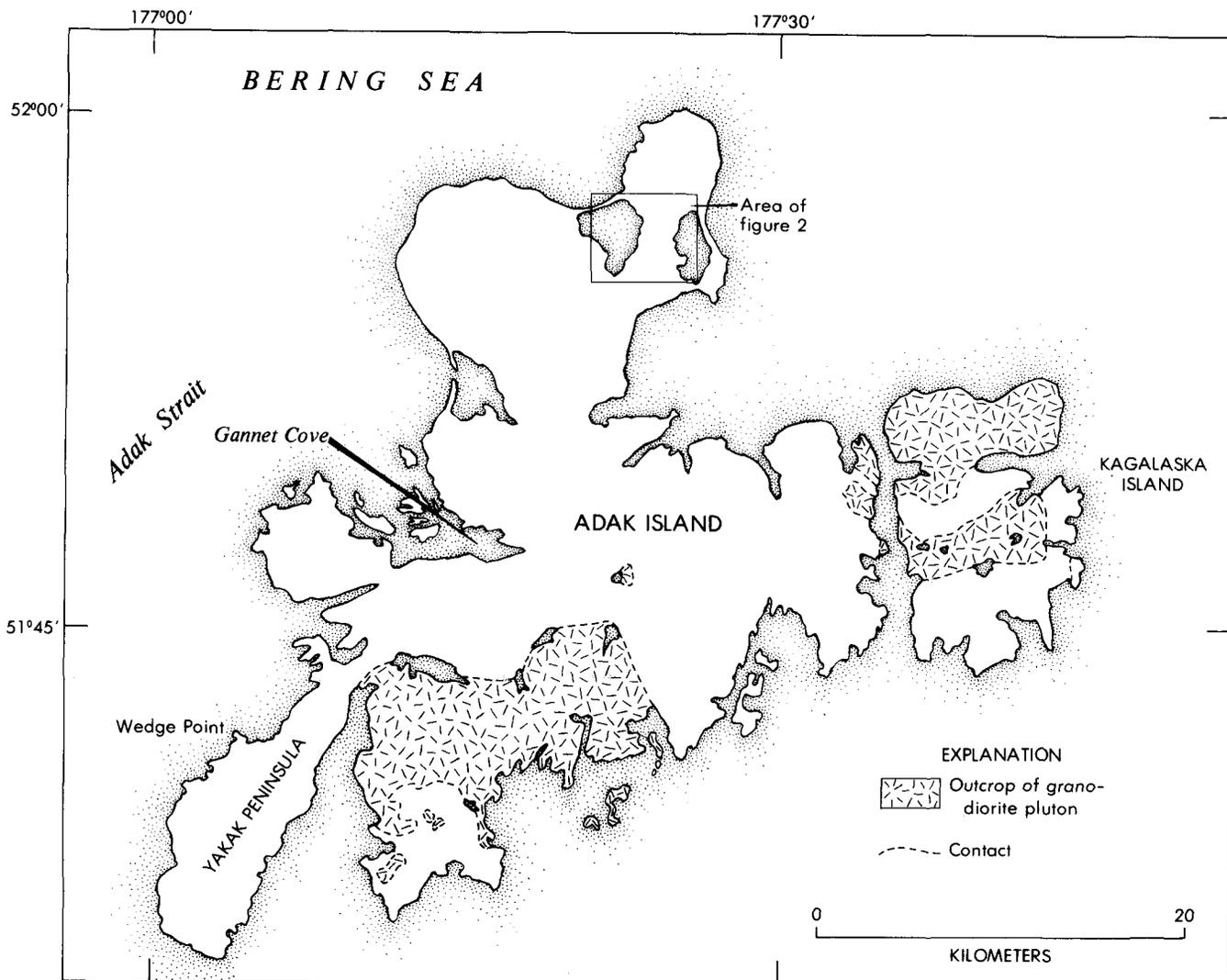


FIGURE 1.—Location of outcrops of granodiorite plutons on Adak and Kagalaska Islands in the central Aleutian Islands. Area of figure 2 is indicated by rectangle, Wedge Point area is shown in figure 3.

Here we present information on the petrology, mineralogy, stratigraphy, and depositional environments of the Andrew Lake Formation and the sedimentary and pyroclastic rocks at and near Wedge Point. We also assess the potential of these rocks as sources of hydrocarbons. We define mineral assemblages formed by hydrothermal processes as distinguished from assemblages developed by regional low-grade metamorphism. We speculate on the significance of the Paleocene history of Adak Island in the regional development of the Aleutian island arc and the early Tertiary plate-tectonic interaction of the Kula ridge with the Aleutian subduction zone.

ACKNOWLEDGMENTS

We thank Capt. T. P. Driver, commanding officer of U.S. Naval Station, Adak, for permission to work on the Naval Station and Comdr. Elton Himes for

providing transportation and logistic support for fieldwork. The U.S. Naval Special Service Corps provided logistic support for our works on Yakak Peninsula. H. N. Meeks of the National Oceanographic and Atmospheric Administration Observatory, Adak, provided a vehicle during part of our work. Paul T. Fuller was our able field assistant. C. E. Gutmacher provided X-ray diffractograms and processed a sample for K-Ar dating; G. B. Dalrymple made the K-Ar age determination. John Barron, Kristin MacDougall, Richard Poore, William Sliter, Fred May, and Louie Marincovich searched, often fruitlessly, for fossils. Kam Leong determined the Fe content of three samples by atomic absorption techniques. A. J. Koch, of Mobil Oil Corp., and George Claypool, U.S. Geological Survey, provided organic geochemical analyses and interpretation. We benefited from review

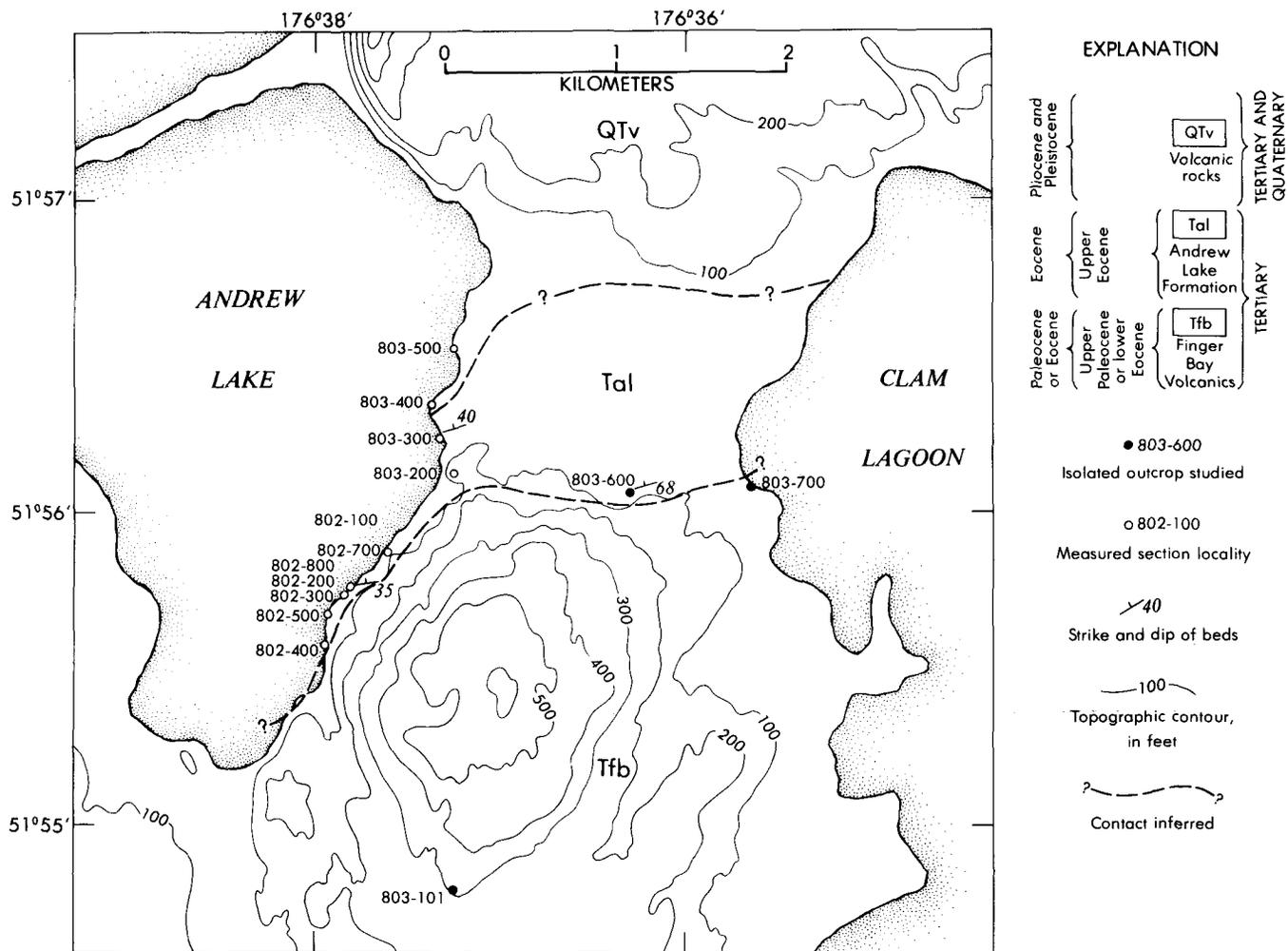


FIGURE 2.—Sample locations and topography of Andrew Lake area, northern Adak Island. (Note that No. 803-600, for example, includes all samples from 600 through 699.) Measured sections are keyed to figure 4. Base from Coats (1956).

by and helpful comments of R. R. Coats, D. W. Scholl, D. A. Swanson, M. S. Marlow, and A. K. Cooper, U.S. Geological Survey; Yotaro Seki, Saitama University, Japan; and A. C. Waters, University of California at Santa Cruz.

ANALYTICAL PROCEDURES

Bulk rock samples and mineral separates were powdered and examined with a Norelco¹ X-ray diffractometer. Most rock samples were cut into thin sections for textural and mineralogical study. Three samples were analyzed for iron content with an atomic absorption spectrophotometer.

ANDREW LAKE FORMATION

Scholl and others (1970) defined and briefly described the Andrew Lake Formation. They suggested

¹ Any use of trade names in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

that it is more than 850 m thick, although only about 40 m of section is actually exposed in quarries and low cliffs along the east shore of Andrew Lake (figs. 2 and 4). An additional 30 m of sedimentary and pyroclastic rocks crops out south of the south limit of the Andrew Lake Formation as described by Scholl and others (1970). Although this lower section is only sparsely fossiliferous and its age is a matter of conjecture, we include it as part of the Andrew Lake Formation. Even with the addition of this section, the total thickness of the formation may not be greater than 800 m (fig. 4).

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

A composite stratigraphic section of the Andrew Lake Formation (fig. 4) compiled from outcrops located on figure 2 shows that the lower half of the section consists mainly of volcanoclastic sedimentary rocks. Volcanic sandstone and silty sandstone are most common, but they range from unsorted sandy

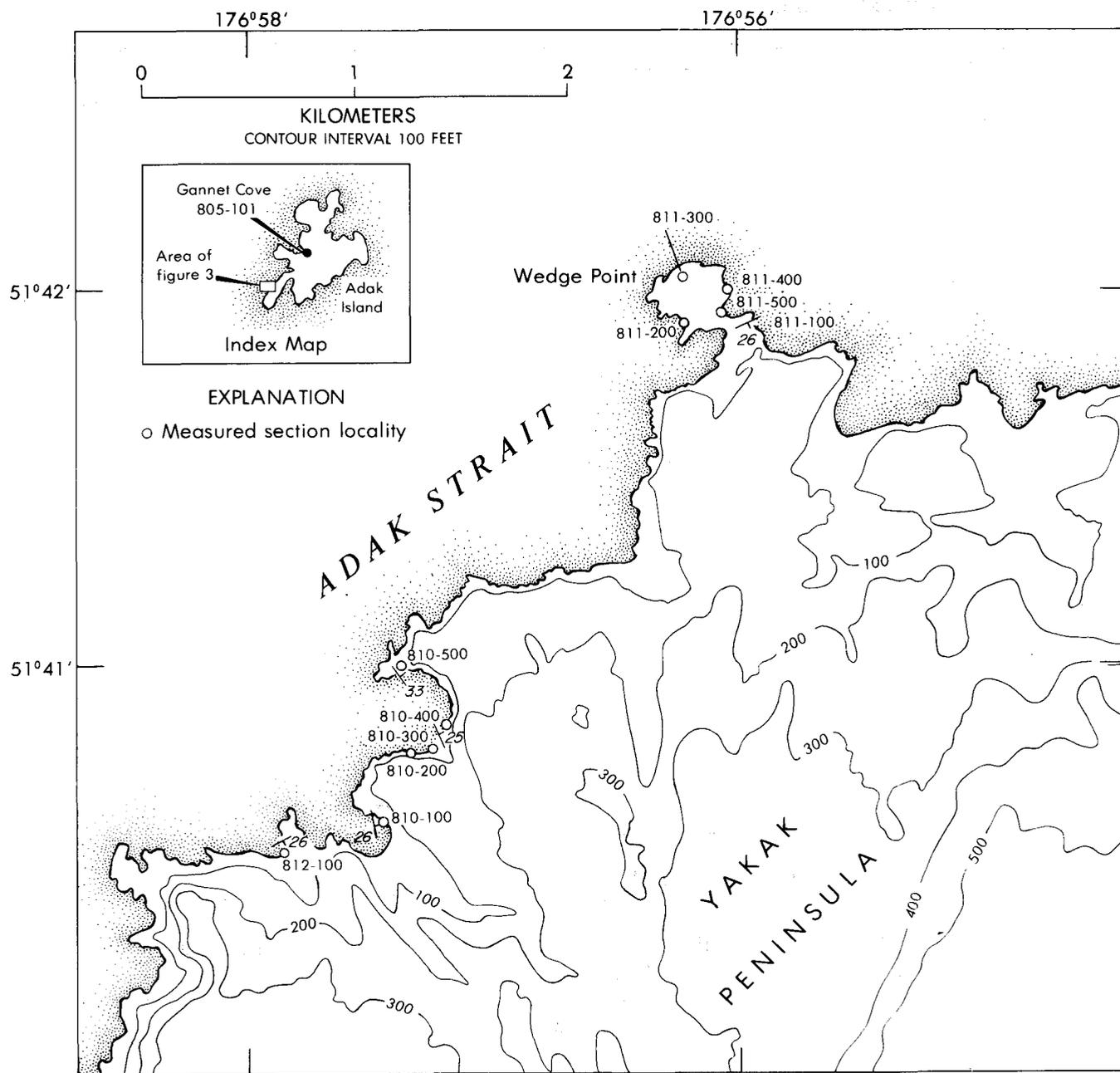


FIGURE 3.—Sample locations and topography near Wedge Point, Yakak Peninsula, southwest Adak Island. Measured sections are keyed to figure 4. Note location of station 805-101 at Gannet Cove, western Adak Island (inset). Base from Fraser and Snyder (1959).

conglomerate to tuffaceous mudstone. Diatoms are rare in these rocks. Intercalated devitrified ash-fall tuff attests to coeval volcanism. Numerous dikes and sills cut this part of the Andrew Lake Formation. Descriptions of the samples studied are given in table 1, in stratigraphic order.

Overlying this relatively coarse grained clastic section are the only richly fossiliferous lower Tertiary strata known on Adak Island (fig. 4). These

strata mark the lower contact of the Andrew Lake Formation as defined by Scholl and others (1970). In this section are thin devitrified ash-fall tuff beds interbedded with quartz chert, laminated quartz porcelanite, siliceous shale, laminated pyritic shale, calcareous chert, and the first recognized occurrence known to us of bedded quartz chert that contains abundant diatoms.

The stratigraphically highest beds in the Andrew

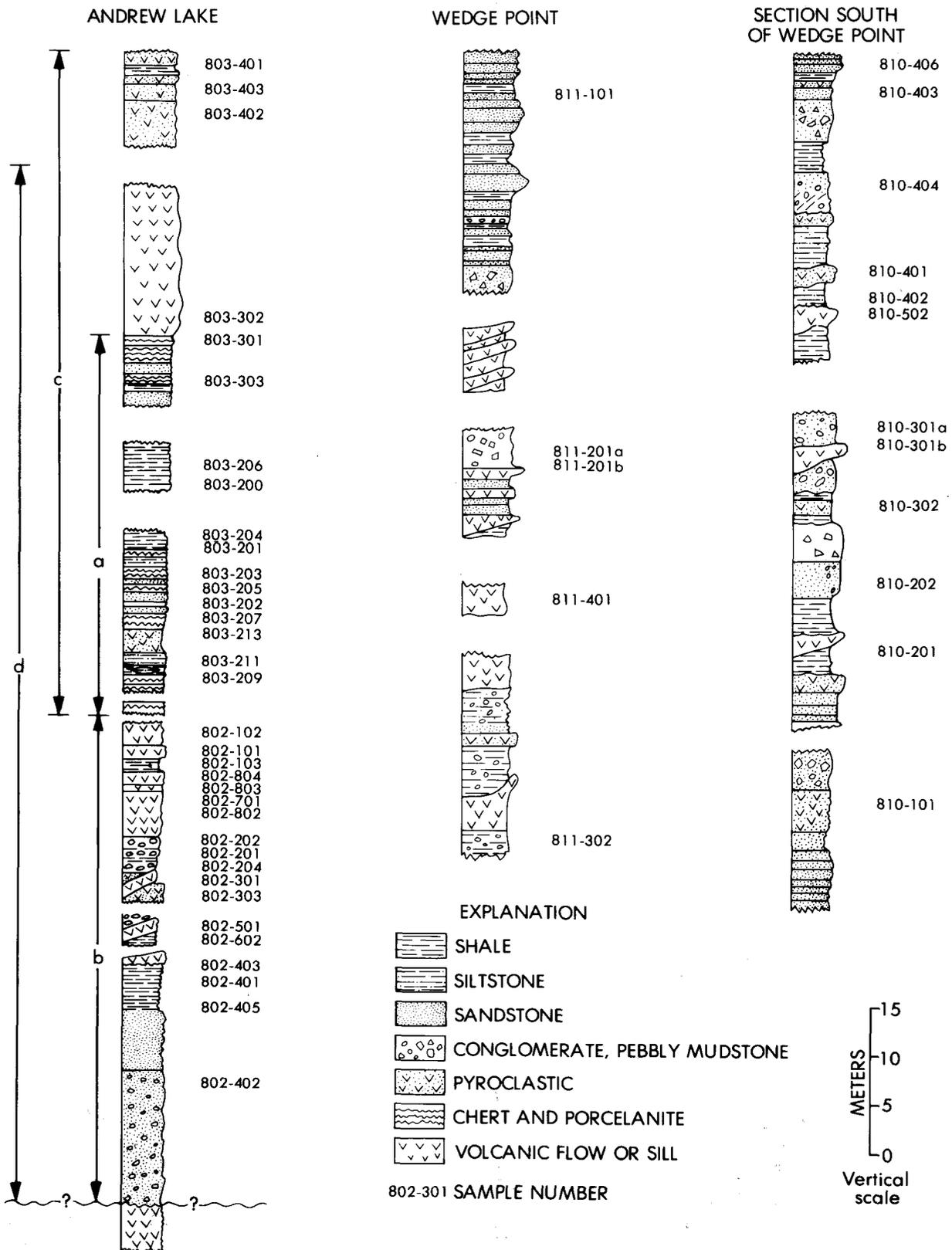


FIGURE 4.—Composite stratigraphic sections of Andrew Lake Formation and two sections near Wedge Point. Sections and sample localities are keyed to figures 2 and 3. Thickness of covered areas (breaks in sections) is unknown. Top part of Andrew Lake section and upper 7 m of Wedge Point section were measured. Queried line marks contact of Andrew Lake Formation with underlying Finger Bay Volcanics. (a) Chert-porcelanite section, (b) section rich with volcanic detritus, (c) Andrew Lake Formation as defined by Scholl and others (1970), and (d) Andrew Lake Formation as redefined.

TABLE 1.—Description of rock samples from the Andrew Lake Formation, Finger Bay Volcanics, and Yakak Peninsula, Adak Island, Alaska

[Locations and formations are keyed to figures 1, 2, and 3. Samples are listed in stratigraphic order starting at the base of the section. A, analcime; Ac, actinolite; Al, albite; Am, amphibole; Au, augite; B, biotite; C, calcite; Ca, chalcedony; Ce, celadonite; Ch, chlorite; Cl, clinoptilolite; Cr, chert; Cz, clinzoisite; E, epidote; F, fossil debris; Fe, iron oxides; H, hypersthene; He, heulandite; Ho, hornblende; I, illite; L, laumontite; M, magnetite; Mn, Mn-dendrites; Mu, muscovite; P, plagioclase; Ph, prehnite; Pr, piemontite; Pr, pyroxene; Py, pyrite; Q, quartz; S, stilpnomelane; Sm, smectite; Sp, sphene; St, stilbite; T, tremolite; V, vermiculite; Vg, altered volcanic glass; VRF, volcanic rock fragments; W, wairakite; Y, yugawaralite; Z, undifferentiated zeolites. Tr., trace. He and St occur only in sample 803 — 701]

Sample No.	Location	Rock type	Major primary constituents	Secondary minerals	Fossils	Comments
802 - 402	Andrew Lake area..	Sandy pebble conglomerate.	VRF, Pr, P, Q, Vg	Al, V, Ch, Q, Fe, L	Diatoms -----	Poorly sorted up to 9 mm.
802 - 405	---do -----	Silty mudstone and fine-grained sandstone.	Q, P, VRF, Pr, Vg	Al, V, Ch, Q, Fe	---do -----	Burrowed, lenses, contorted bedding.
802 - 401	---do -----	Lithic sandstone -----	VRF, P, Vg, Q, I	Q, V-Ch, Ce, Cl, Ch, Fe, Al	Barren -----	
802 - 403	---do -----	Lithic sandstone and siltstone.	VRF, Vg, I, P, Q	Ch, L, Q, Fe, V-Ch, Cl, S	Rare fragments..	Pods of vitric ash, lenses, contorted bedding.
802 - 602	---do -----	Porphyritic dike -----	P, Pr, Q	V-Ch, L, Q, Fe, Al	Not looked for --	
802 - 501	---do -----	Lithic sandstone and sandy and silty mudstone.	VRF, Vg, Pr, Q, P	Q, V-Ch, Ch, L, Al, Fe	Barren -----	Lenses of organic matter, burrowed.
802 - 303	---do -----	Pebble conglomerate and silty mudstone and sandstone.	Vg, VRF, Q, I, Pr	L, V-Ch, Q, Fe	---do -----	Grains compact-penetrates. Conglomerate is well graded. Clasts to 12 mm.
802 - 301	---do -----	Pumiceous ash-fall tuff?.	Vg, P, Pr	L, Q, V, Fe	---do -----	Nearly totally replaced by laumontite.
802 - 204	---do -----	Pebbly sandstone -----	VRF, P, Au, Q, Vg	Q, V, Ch, L, Al, Ph, S, Fe	---do -----	Very poorly sorted clasts to 13 mm.
802 - 201	---do -----	Fine-grained sandstone and silty mudstone.	VRF, P, Q, Pr, Ac, E, C, Ph	Q, V-Sm, L, Al, Fe	---do -----	Sandy layers are poorly sorted and crudely graded.
802 - 202	---do -----	Fine-grained lithic sandstone.	P, VRF, Au, Ac, E, C, Mu	Q, Al, V, Ch, Fe, L	---do -----	
802 - 802	---do -----	Volcanic sill -----	P, Q, Au, H, B	Ch, V	Not looked for --	K-Ar date 14 m.y.
802 - 701	---do -----	Volcanic flow? or sill --	P, Pr, Q, B	Q, V, Ch	---do -----	Pillowlike structures.
802 - 803	---do -----	Altered vitric tuff -----	P, Vg, Q	V, Sm, Q	Barren -----	
802 - 804	---do -----	Volcanic siltstone -----	Q, P, Vg	Q, Z, Ch, V, C, Fe	Fragments -----	Pods of tuff.
802 - 103	---do -----	Tuffaceous mudstone -----	Q, P, Vg, Pr, B	Q, C, Ch	Diatoms and radiolarians.	
802 - 101	---do -----	Tuff? -----	P, Vg, Pr, Q	V-Ch, Fe, Al, Q, Ch	Benthic foraminifers.	Completely altered, 14 cm below dike.
802 - 102	---do -----	Volcanic dike -----	P, Pr, Q	V, Ch, Q	Not looked for --	
803 - 209	---do -----	Black chert -----	Q	Q, Tr, Z	Dinoflagellate ---	Much organic debris.
803 - 211	---do -----	Vitric tuff -----	Vg, P	Sm, Cl	Barren -----	Friable.
803 - 213	---do -----	---do -----	Vg, P, Pr	Sm-V, Ce, Fe, Q	---do -----	Do.
803 - 207	---do -----	Chert and porcelanite --	Q, P, I, F	Q, Fe, Ch	See table 2 -----	Late Eocene, upper bathyal.
803 - 202	---do -----	Calcareous chert -----	Q, P, F	Q, C	Diatoms, radiolarians.	
803 - 205	---do -----	Chert and porcelanite --	Q, P, F	Q, Py, Mn	Microfossil molds.	Burrowed, laminated.
803 - 203	---do -----	---do -----	Q, P, F	Q, Py, Mn	---do -----	Laminated.
803 - 201	---do -----	---do -----	Q, P, F	Q, Py, Mn	---do -----	
803 - 204	---do -----	Siliceous shale -----	?	?	Benthic foraminifers.	Cretaceous through Oligocene.
803 - 200	---do -----	Pyritic silty shale -----	Q, P, I, F	Q, C, Py, Ce, V	See table 2 -----	Laminated, late Eocene, upper bathyal.
803 - 206	---do -----	Black silty shale -----	?	?	Barren -----	
803 - 303	---do -----	Diatom chert and siliceous shale with chert nodules.	Q, P, F, Am, VRF	Q, V-Ch, C, Fe	Diatoms, radiolarians, foraminifers.	Vermiculite clay nodules, shale is laminated.
803 - 301	---do -----	---do -----	Q, P, F, VRF	Q, C, V-Ch, Fe	Diatoms, radiolarians, foraminifers, and fish.	Laminated shale, hematite pseudomorphs after pyrite.

Lake Formation described by Scholl and others (1970) include aquagene tuff, ash-fall tuff and possibly ash-flow tuff, and volcanic dikes (fig. 4). These pyroclastic rocks differ texturally and mineralogically (table 1) from strata in the lower part of the formation. Mild alteration of framework grains and traces of sideromelane(?) that has not devitrified contrast with the greater alteration shown by underlying rocks and suggest that this uppermost section

may be younger than the underlying, more altered part of the section. Therefore, both the lower and upper contacts of this formation as originally proposed by Scholl and others (1970) are redefined here.

We redefine the base of the Andrew Lake Formation exposed along the southeast shore of Andrew Lake (fig. 2) to include the conglomerate at locality 802-400 (figs. 2 and 4); the underlying silicified

TABLE 1.—Description of rock samples from the Andrew Lake Formation, Finger Bay Volcanics, and Yakak Peninsula, Adak Island, Alaska—Continued

Sample No.	Location	Rock type	Major primary constituents	Secondary minerals	Fossils	Comments
803 - 302	Andrew Lake area	Volcanic dike	P, Pr	Al, Ch, V	Not looked for	
803 - 403	do	Aquagene tuff	Vg, P, VRF, Pr	Q, W, V, Ce, rare C	do	Unaltered minerals and some glass (?).
803 - 403	do	Ash-flow tuff	Vg, VRF, P, B, Au, Cz	Q, W, Sm, Cl, Ch, C, V	do	Unaltered minerals.
803 - 401	do	Ash-fall tuff	Vg, P, B, Am	Q, Cl, W, V, Sm	Barren	Unaltered minerals and some glass (?).
803 - 601	do	Clayey siltstone	Q, P, F	Ch, V-Ch, Fe, Q	Foraminifers, echinoid.	
803 - 602	do	Lithic sandstone	P, Q, VRF	V-Ch, C, Q, Ch, Al	Barren	Baked by nearby dike.
803 - 604	do	do	P, VRF, Q	V-Ch, C, Q, Ch, Al, Fe	do	Do.
810 - 101	South of Wedge Point.	Welded tuff	Vg, P, Pr	Y, Ch, Ce, Fe, I-Mu, L	do	Purple with green mottling.
810 - 201	do	Volcanic dike	P, Pr, Vg	Vesicles: Q, S-Ce-Ch, L or C; Matrix: Fe, C, Q	Not looked for	
810 - 202	do	Lithic sandstone	VRF, P, Pr	Y, Q, Al, Ch, Fe	Barren	Poorly sorted, compact, grains penetrate.
810 - 302	do	Tuff	?	?	do	
810 - 301a	do	Pebbley mudstone	Vg, P, Au, VRF	Y, Q, Fe, Ch, V, Tr, L, Al	do	Lahar.
810 - 301b	do	Volcanic flow	P, Au	Vesicles: W, S, L; Matrix: Al, Fe, I	Not looked for	
810 - 502	do	Sandy shale	?	?	Barren	
810 - 402	do	do	?	?	do	
810 - 401	do	Ash-flow tuff	Vg, Au, P	I, Ch, V, Ce, C, Fe, Tr, Y, L	Not looked for	Slightly welded.
810 - 404	do	Pebbley mudstone	Vg, P, W	An, Q, Ch, Ce, Y(?)	Barren	Pumiceous lahar.
810 - 403	do	Lithic sandstone	VRF, P, Pr	An, Fe, clays	do	Banded, well sorted, crudely graded.
810 - 406	do	do	VRF, P, Pr, Q	Z, Q, Ch, Fe	do	Poorly sorted, graded.
812 - 104	do	Silicified ash	Vg, P	Q, Ch, Fe, C	Spicules?	
811 - 302	Wedge Point	Pebbley mudstone	?	?	Barren	
811 - 401	do	Volcanic dike	Au, P, Sp, M	Vesicles: Q, Ch+S+Ce, L, Q, Tr, Pr, E; Matrix: Q, L, Al, E, Fe, Ch, I	Not looked for	More than 50 percent altered to quartz and laumontite.
811 - 201a	do	Pebbley mudstone	Vg, P, Pr, M	Q, C, Ch, S, Ce, Fe, A	Barren	Pumiceous.
811 - 201b	do	Volcanic dike	P, Au, M	Vesicles: L, S+Ch+L, Q; Matrix: Q, Fe, Ch	Not looked for	
811 - 101	do	Silty sandstone	Vg, P, M, Au, Q	Q, Fe, Ce, I-Mu, Y, L, A	Barren	Poorly sorted, pumiceous.
811 - 201	do	Volcanic wacke	VRF, P, Pr, Q	Al, Q, Y, Fe, L, Ch	do	
803 - 101	Southeast of Andrew Lake.	Lithic sandstone	P, Q, B, VFR, Ho, Cr	Ac-T, E, Q, Fe, Ch, V	do	Finger Bay Volcanics, compact.
805 - 101	Gannet Cove	Quartzite and epidosite	Q, P, Cg, F, B	E, C, Q, Mu, Fe, Ch, Pi?	Ghosts of microfossils.	Finger Bay Volcanics, poorly sorted.
803 - 701	Clam Lagoon	Hydrothermal vein	W, Ca, V, Cl, He, St	Not looked for	Not looked for	Vein cuts Finger Bay Volcanics.

volcanic rocks are assigned to the Finger Bay Volcanics. The top of the formation is in the area covered by tundra between outcrop localities 803-300 and 803-400 (figs. 2 and 4).

Fossils (table 2) indicate that the strata of the redefined Andrew Lake Formation were deposited in a marine environment, probably at water depths between 200 and 500 m. Sediments were reworked by bottom currents and by infauna. Lenses containing diatoms or devitrified ash are locally abundant; however, laminated porcelanite, black pyritic shale, and laminated shale from the middle part of the section suggest that the depositional basin was for a time "starved" or cut off from active terrigenous sedimentation. Consequently, mainly biogenic material accumulated, although an active infauna was not present.

Other sedimentary structures and current-direction indicators are rare. They include ripple lamina-

tions and poorly developed graded bedding. Sandstone beds are graded and have flute casts, and sandstone and shale sequences are rhythmically bedded, which suggests deposition by turbidity currents. Rare crossbedding indicates eastward current flow. Deposition of most of the Andrew Lake Formation is ascribed to a combination of biogenic-pelagic, turbidity-current, hemipelagic, and pyroclastic processes.

SECONDARY MINERALS

Most rocks of the Andrew Lake Formation are silicified and in part altered to clay minerals and iron oxides (table 1). In most samples, plagioclase of intermediate anorthite content is partly altered to albite. In the lower part of the section where volcanogenic sedimentary rocks, pyroclastic debris, and volcanic dikes and sills are abundant, quartz and

TABLE 2.—Foraminifers from the Andrew Lake Formation
 [Fossils identified by Kristin McDougall, R. Z. Poore, and W. V. Sliter]

Sample No.	Benthic forams	Other microfossils	Age range	Depth of water
802-101	<i>Bathysiphon</i> sp. -----	-----	Indeterminate	-----
803-200	<i>Cyclammmina pacifica</i> ? -----	Echinoid spines -----	Late Eocene	Upper bathyal.
	<i>Cyclammmina</i> sp. -----	Radiolarians -----	-----	-----
	<i>Dentalina</i> sp. -----	-----	-----	-----
	<i>Eponides</i> sp. -----	-----	-----	-----
	<i>Gyroidina soldanii</i> d'Orbigny -----	-----	-----	-----
	<i>Lenticulina</i> sp. -----	-----	-----	-----
	<i>Valvulineria</i> sp.? -----	-----	-----	-----
803-207	<i>Bathysiphon eocenicus</i> -----	Echinoid spines -----	Late Eocene	Upper bathyal.
	<i>Bathysiphon</i> sp. -----	Fish debris -----	-----	-----
	<i>Cyclammmina pacifica</i> Beck -----	Radiolarians -----	-----	-----
	<i>Dentalina</i> sp. -----	-----	-----	-----
	<i>Eponides</i> sp. -----	-----	-----	-----
	<i>Gyroidina soldanii</i> d'Orbigny -----	-----	-----	-----
	<i>Lenticulina</i> sp. -----	-----	-----	-----
	<i>Melonis umbilicatus</i> (Montague) -----	-----	-----	-----
803-601	<i>Cyclammmina</i> sp. -----	Echinoid spines -----	Intermediate	-----
803-204	<i>Bathysiphon eocenicus</i> ? -----	-----	Cretaceous	-----
	<i>Rhabdammina eocenica</i> ? -----	-----	through	-----
	-----	-----	Oligocene.	-----

laumontite occur as interstitial cement and replace volcanic debris along with vermiculite, chlorite, smectite² and vermiculite-chlorite (randomly inter-layered). Some volcanic rock fragments are almost completely altered to iron oxides and clays. Locally calcite, analcime, clinoptilolite, and stilpnomelane replace volcanic debris.

Three samples (802-202, -201, -204 in fig. 4) from the upper part of this section rich in volcanic detritus contain abundant actinolite, epidote, chlorite, and calcite. These minerals, commonly found in greenschist-facies metamorphic rocks, occur as detrital minerals in these three samples (table 1). Adjacent to dikes and sills, however, secondary prehnite and epidote have formed (for example, prehnite in sample 802-204, table 1).

Because mineralogically unstable volcanic debris is less abundant, fewer secondary minerals characterize the chert-porcelanite part of the section. Quartz and minor calcite and pyrite are the most important secondary minerals. Quartz indiscriminately replaces most sediment components and fills all available void space; thus abundant siliceous shale and porcelanite are produced. Calcite replaces quartz and is therefore a relatively late stage mineral.

Ash-fall tuff in the Andrew Lake Formation has altered to smectite and minor clinoptilolite. In places smectite was subsequently converted to vermiculite.

² Smectite is the internationally accepted group name for the clay minerals that include montmorillonite, nontronite, and saponite (Brindley and Pedro, 1975). It is used as a general term.

Locally vermiculite, chlorite, hematite, and celadonite replace volcanic detritus (table 1).

Pyroclastic rocks that overlie the Andrew Lake Formation as redefined herein contain unaltered framework grains, but most of the glassy volcanic material is replaced by wairakite and to a lesser extent by clinoptilolite, quartz, and celadonite. Vermiculite, smectite, chlorite, and iron oxides are present; calcite is rare (table 1). Plagioclase is of intermediate composition. Celadonite in this part of the section is blue, whereas lower in the section it is green.

Secondary mineral assemblages or mineral facies in the stratigraphic section can indicate the history of burial metamorphism of the rocks. Accordingly, quartz, vermiculite, vermiculite-chlorite, smectite, chlorite, iron oxides, and celadonite are ubiquitous. Clinoptilolite is present in places but is most common at the top. Stilpnomelane and laumontite are in the lower part; wairakite occurs near the top of the section. Calcite and pyrite are mainly at midsection (table 1).

AGE

The Andrew Lake Formation was assigned a middle or late Eocene age by Scholl and others (1970) on the basis of microfossils and megafossils. Our collections of benthic foraminifers (table 2) indicate that the Andrew Lake Formation was deposited during the late Eocene, virtually identical to the foraminiferal age assigned in Scholl and others

TABLE 3.—K-Ar data and age for an andesite sill, Andrew Lake Formation

[Potassium measurements by A. Berry; argon measurement and age calculation by A. Berry and E. Sims]

Sample No.	Mineral	Percent K ₂ O	⁴⁰ Ar _{rad} (moles/g)	$\frac{^{40}\text{Ar}_{\text{rad}}}{^{40}\text{Ar}_{\text{total}}}$	Calculated age (millions of years)
802 - 802	Plagioclase	0.079	1.640×10^{-12}	0.04	14.4 ± 3.5

⁴⁰K decay constants: $\lambda_c = 0.572 \times 10^{-10}/\text{yr}$, $\lambda_{c'} = 8.73 \times 10^{-10}/\text{yr}$, $\lambda_{\beta} = 4.905 \times 10^{-10}/\text{yr}$. Abundance ratio $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4}$ percent atomic.

(1970). According to Berggren (1972), late Eocene represents an absolute age of 37.5 to 43.0 m.y.

A K-Ar date on fresh plagioclase from an andesite sill cutting the Andrew Lake Formation was 14.4 ± 3.5 m.y. (table 3).

We speculate that the pyroclastic rocks that overlie the Andrew Lake Formation as redefined, but included in the formation by Scholl and others (1970), are part of a younger series of volcanic rocks. These strata are structurally concordant with the lower part of the formation, but the unaltered framework grains and only mild alteration of glass shards differ markedly from the relatively high degree of alteration of samples from only slightly lower stratigraphically. Similar mild alteration is typical of other Neogene volcanic rocks on Adak; for example, the sill (802-802) cutting the Andrew Lake Formation dated by the K-Ar method as middle Miocene (table 3). Perhaps these little-altered pyroclastic rocks are associated with the intrusion of Miocene granodiorite plutons and related dikes and pyroclastic deposits (Fraser and Snyder, 1959). However, eruption of the pyroclastic rocks at any time after the Eocene cannot be ruled out.

HYDROCARBON POTENTIAL

Two samples of shaly siltstone were analyzed for TOC (total organic carbon), EOM (chloroform extractable bitumen), and R_o (vitrinite reflectance). These quantities, as well as EOM/TOC, are listed in table 4. Sample 803-204 (fig. 4 and tables 1 and 4) contains 0.41 weight percent of TOC, the highest value recorded for any rocks on Adak Island. This value, however, is still below the 0.50 weight percent quantity generally considered to separate a possible source rock from one with no source-rock potential. The R_o value of 2.1+ indicates that sample 802-804 has been heated well beyond the level of crude oil stability (A. J. Koch, written commun., 1976). A low EOM/TOC ratio can be interpreted as resulting from the "cracking" of organic material; the break-up of organic compounds probably resulted from the

TABLE 4.—Organic geochemistry of Tertiary sedimentary rocks from Adak Island

[Analyses of total organic carbon (TOC) by U. S. Geol. Survey Organic Geochemistry Laboratory, Lakewood, Colo. Analyses of chloroform extractable bitumen (EOM), vitrinite reflectance (R_o), and EOM/TOC by Mobil Oil Corp., Dallas, Tex.]

Sample No.	Location	TOC (weight percent)	EOM (ppm)	R_o	EOM/TOC (percent)
803 - 204	Andrew Lake	0.41	28.6	2.1+	0.70
803 - 206	do	.04	28.7	*	7.10
810 - 302	Wedge Point	.05	44.3	*	8.90
810 - 402	do	.09	40.2	*	4.50
810 - 502	do	.07	29.3	*	4.20
811 - 302	do	.04	26.4	*	6.60

* Insufficient organic carbon for vitrinite reflectance measurement.

heat produced by nearby intrusions such as the numerous dikes and sills observed in outcrop.

Sample 803-206 has a very low TOC content, but the EOM/TOC ratio indicates that it has not been subjected to excessive heat. A low TOC content means that there probably never was a significant quantity of organic material present. Attempts to recover organic residue for measurement of R_o were unsuccessful.

YAKAK PENINSULA STRATA (WEDGE POINT AREA)

Fraser and Snyder (1959) mapped a section of sedimentary, volcanic, and volcanoclastic strata on the west side of Yakak Peninsula (fig. 3) as part of the Finger Bay Volcanics. On the basis of lithologic composition, degree of alteration and induration, and the types of secondary minerals present (see below), we propose that these strata are temporally equivalent to the Andrew Lake Formation. Study of the mineralogy and petrology of samples from two stratigraphic sections, one immediately south of and one at Wedge Point (fig. 3), complements the reconnaissance work done by Fraser and Snyder.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

The section south of Wedge Point (figs. 3 and 4) consists predominantly of interbedded sandstone, shale, and pebbly mudstone, with minor ash-flow and ash-fall tuff (including slightly welded tuff); volcanic dikes cut the section. Sandstone beds are primarily lithic arenite but include lithic to feldspathic arenite and wacke. Virtually all lithic grains are volcanic rock fragments, generally subrounded. Plagioclase, pyroxene, and locally quartz are other common framework grains. Poorly sorted rocks abound, but graded, layered, and well-sorted beds occur near the top of the section. Sandstone is com-

monly cemented by laumontite, yugawaralite,³ iron oxides, or clays.

Pebbly mudstone beds contain mostly subangular grains, although a complete range of grain roundness is present. Again, the framework grains are dominantly volcanic rock fragments and, in some samples, are primarily pumiceous. These poorly sorted rocks are texturally like mudflows and are probably lahars. The mudflow units are as much as several tens of meters thick, and they include rock fragments up to 1 m in diameter.

Ash-flow tuff is purplish to gray, commonly with a green mottled surface reflecting replaced volcanic glass globules (replaced collapsed pumice lapilli?). Texturally, it appears massive to weakly flow banded. Sample 810-101 (figs. 3 and 4; table 1) is mostly glass globules and flattened pumice fragments (greater than 3 mm) replaced by yugawaralite. Sample 810-401 has pumice with an elongation ratio of 20:1. Large plagioclase and augite glomerocrysts (Carlisle, 1963, p. 58) are present. The groundmass appears to be collapsed pumice and glass shards replaced by illite or muscovite.

The section includes many porphyritic volcanic dikes altered to zeolites, quartz, and iron oxides. Vesicles and amygdules are filled with zeolites, quartz, and clays. Phenocrysts are mostly plagioclase, partly or wholly altered to albite, and pyroxene that is locally fresh.

The section at Wedge Point (figs. 3 and 4) is similar to the one to the south just described but is capped by 7 m of alternating sandstone (volcanic wacke) and shale; two pebbly sandstone beds occur in this section. Wacke makes up 93 percent of this 7-m section and consists of beds 3 to 130 cm thick (average 47 cm), whereas the 7 percent of shale consists of beds 2 to 12 cm thick (average 5.4 cm). In general, beds increase in thickness up section. Framework grains are mostly volcanic fragments, plagioclase, pyroxene, and altered volcanic glass. Samples rich in relict volcanic glass also contain abundant zeolites. The matrix is made up mostly of clays, iron oxides, and fine-grained counterparts of framework grains.

Relative to the section south of Wedge Point, intrusive bodies at Wedge Point are more highly altered. From 50 to 75 percent of the host volcanic rock may be altered to zeolites, quartz, and clays.

The presence of ash-flow tuff and boulder lahars and the apparent absence of microfossils suggest

that the rocks at Wedge Point were deposited in a subaerial to shallow marine environment and that volcanism was active near the site of deposition. Fiske (1963) and Fiske and Matsuda (1964) have demonstrated that submarine ash-flow tuff is not welded. Rocks at Wedge Point must therefore be, in part, subaerial deposits. Further, the presence of graded lithic arenite and sequences of alternating lithic wacke and shale suggest turbidity-current deposition; if so, Wedge Point rocks are in part subaqueous deposits (probably shallow marine). No freshwater fossils or lacustrine deposits were found at Wedge Point.

SECONDARY MINERALS

Porphyritic basaltic and andesitic rock fragments are altered to iron oxides (mostly hematite) and clay minerals (dominantly chlorite and illite). Plagioclase is altered to albite that has approximately parallel extinction and little or no relict zoning. In contrast, clinopyroxene is commonly unaltered. Much pumice is replaced by vermiculite and chlorite. Other glassy volcanic fragments are replaced dominantly by zeolites such as yugawaralite, analcime, and laumontite, and to a lesser extent by quartz, illite, chlorite, celadonite, hematite, vermiculite, and smectite. The rare zeolite, yugawaralite, is the most common zeolite in these rocks on Yakak Peninsula.

Sandstone is cemented by analcime, yugawaralite, laumontite, chlorite, illite, and hematite. Thin (0.005-0.1 millimeter) clay films coat all grains in some beds of arenite. The framework grains are compact and penetrate adjacent grains, and the remaining pore spaces (commonly very small, maximum 0.4 mm² in cross section between grains) are filled with a zeolite such as analcime in sample 810-403 (figs. 3 and 4; table 1). These observations mean that the grains acquired their clay rim after deposition and were subsequently compacted (probably by deep burial) before cementation by zeolite. The zeolite cement is a relatively late occurrence. Galloway (1974) suggested that these diagenetic changes could occur after 300 to 1200 m of burial. He showed that the surface coatings of authigenic clay were the result of mobilization of silica and aluminum from the volcanic debris.

The groundmass of dikes and sills is replaced by quartz, laumontite, analcime, stilpnomelane, albite, iron oxides, chlorite, illite, and calcite; calcite is the latest mineral. Minerals found in vesicles and amygdules suggest the following paragenetic sequence: quartz (occasionally replaced by laumontite), granular material (unidentifiable), analcime, phyl-

³Yugawaralite, a rare calcium zeolite, has been reported from only one other locality in North America, near Fairbanks, Alaska (Eberlein and others, 1971). It has also been reported from Heinabergsjökull, Iceland (Barrer and Marshall, 1965) and from Japan (Sakurai and Hayashi, 1962; Seki and Okumura, 1968; Sameshima, 1969; Seki and others, 1969).

losilicates (stilpnomelane, chloride, celadonite, rarely vermiculite or hematite), laumontite, phyllosilicates again (minor), and rarely quartz, calcite, pyrite, or epidote. The filling of an amygdule may begin any place in this sequence, and four or five different minerals may occur in one amygdule. The granular material listed above is a very fine grained, high-relief, highly birefringent mineral that may be calcite or epidote. It occurs as a thin and at places discontinuous band separating the first and second minerals formed in the vesicles. Laumontite and terminated quartz crystals more than 2 cm long suggest that these minerals formed from hydrothermal solutions.

AGE

No fossils were recovered from the strata on Yakak Peninsula. From the lithologic composition, and degree of alteration and induration, we infer that these strata are probably temporal equivalents of the Andrew Lake Formation.

HYDROCARBON POTENTIAL

Four samples from the Wedge Point area (table 4) show consistently low values of total organic carbon and are not considered to be potential source rocks for petroleum. No organic residue for determination of vitrinite reflectance was removed from any of these samples.

FINGER BAY VOLCANICS

Coats (1956) and Fraser and Snyder (1959) described the Finger Bay Volcanics as pervasively altered to chlorite, albite, epidote, and silica. We examined two samples (803-101 and 805-101) of sandstone from the Finger Bay Volcanics (fig. 2; fig. 3, inset) for comparison with sedimentary rocks of the Andrew Lake Formation and of Yakak Peninsula.

Sample 803-101, collected from a quarry southeast of Andrew Lake, is a compact, poorly sorted feldspathic arenite. The main framework grain is plagioclase with accessory quartz, biotite, volcanic rock fragments, and chert. Silica and less abundant clays cement the rock. Abundant epidote, quartz, and actinolite-tremolite replace pyroxene(?) and feldspar grains and fill veins (table 1). Plagioclase is altered to albite. Chlorite, vermiculite, and hematite are less abundant secondary minerals.

Quartz sandstone, quartzite, and minor epidosite are found at Gannet Cove on the west coast of Adak Island (sample 805-101, fig. 3, inset). Quartz, epidote, and muscovite are secondary minerals that now

compose the bulk of the rocks. Piemontite, calcite, chlorite, iron oxides, and illite are minor secondary minerals. Granular quartz and deeply corroded and replaced plagioclase are probably the only primary grains remaining. Faint structures are reminiscent of glass shards, collapsed pumice, and microfossils. Rare chlorite spherulites occur. Although the Finger Bay Volcanics is highly altered, it is not penetratively deformed. Open folds with dips generally less than 40° occur (Fraser and Snyder, 1959).

METAMORPHISM

Secondary mineral assemblages (Fraser and Snyder, 1959) suggest that the Finger Bay Volcanics was subjected to regional greenschist-facies metamorphism. The diagnostic mineral assemblages range from actinolite- or tremolite-epidote-chlorite-albite-quartz to epidote-quartz-muscovite-chlorite-albite (table 1). Prehnite and pumpellyite mineral assemblages, indicative of lower temperature grades than actinolite-greenschist facies (Coombs, 1953; Seki, 1969, Coombs and others, 1970), appear in the Finger Bay Volcanics (Fraser and Snyder, 1959), although the reconnaissance nature of the work by Fraser and Snyder precludes delineation of a coherent regional pattern of metamorphic facies. Certainly, the actinolite and epidote greenschist assemblages appear to be dominant on Adak Island.

It is not clear whether emplacement of granodiorite plutons contributed significantly to metamorphism (contact metamorphism) of the Finger Bay Volcanics or whether metamorphism was dominated by a regional thermal event. Fraser and Snyder (1959) described only a thin zone of contact-metamorphic hornfels adjacent to the plutons. It is worth noting, however, that although some outcrops of the Finger Bay Volcanics and the Andrew Lake Formation are equidistant from exposed plutonic rocks, these formations show significant differences in metamorphic mineral assemblages. More fieldwork is needed to fully distinguish regional patterns from contact metamorphism.

In contrast to the Finger Bay Volcanics, sedimentary and pyroclastic rocks on Yakak Peninsula and the Andrew Lake Formation at Andrew Lake have not been subjected to greenschist- or even zeolite-facies regional metamorphism. These rocks have been moderately altered by low-temperature supergene and hydrothermal processes of the zeolite facies and nowhere show greenschist-facies metamorphism. Thermal metamorphism associated with emplacement of dikes and sills, together with the supergene

and hypogene mineralization, has created a complex milieu of secondary minerals.

AGE

Except for sedimentary rocks of the Andrew Lake Formation, Paleogene rocks of Adak Island are apparently devoid of fossils. Fossil findings indicate that the Andrew Lake Formation accumulated during the late Eocene (37.5–43 m.y. ago; Scholl and others, 1970; table 2). The Finger Bay Volcanics is estimated to be as old as the initial formation of the Aleutian ridge and no younger than the overlying Andrew Lake Formation. The Finger Bay Volcanics therefore formed sometime before the late Eocene (before about 40 m.y. ago) but probably after latest Cretaceous (about 65 m.y. ago) (Marlow and others, 1973; Scholl and others, 1975). The Finger Bay Volcanics and associated sedimentary rocks evolved through a sequence of deposition, burial, regional greenschist-facies metamorphism, uplift, and erosion before the Andrew Lake Formation was deposited. We therefore favor an age representative of the older part of this (40–65 m.y.) timespan, perhaps late Paleocene or early Eocene (about 50 m.y. ago), but rocks may be as old as early Paleocene (60 m.y.). Certainly the episode of regional metamorphism must have ended at least 45 m.y. ago. Unfortunately, it may not be possible to obtain reliable radiometric dates from the Finger Bay Volcanics because of the thermal effects associated with the intrusion of plutonic rocks. The granodiorite on adjacent Kagalaska Island is Miocene (dated as 13.2 and 13.7 m.y.; Marlow and others, 1973; DeLong and others, 1978), approximately the same age as an andesite sill (table 3) cutting the Andrew Lake Formation, and is probably the same age as plutons on Adak.

Available published data (Fraser and Barnett, 1959; Powers and others, 1960; Lewis and others, 1960; Carr and others, 1970 and 1971; Gates and others, 1971) suggest that the oldest exposed rocks on the western Aleutian Islands (Attu, Agattu, Shemya, Amchitka, Rat, Amatignak, Ulak, Tanaga, Kanaga) have undergone variable but mild alteration. Variability of alteration, presence of fresh calcic plagioclase, only weakly altered volcanic glass, and the occurrence of a variety of temperature-sensitive zeolites argue against regional greenschist-facies metamorphisms of the exposed rocks on these islands. Accordingly, the Finger Bay Volcanics on Adak Island appears to be unique among the rocks that crop out on the western Aleutian Islands and may represent the oldest rocks described to date

from these areas. Alternatively, the basement rocks of other Aleutian islands may be the same age as, but were not as deeply buried as the Finger Bay Volcanics on Adak Island.

DISCUSSION

PALEOGENE SEDIMENTATION

Fraser and Snyder (1959) estimated that the exposed section of the Finger Bay Volcanics includes about 70 percent pyroclastic, 20 percent flow, and 10 percent sedimentary rocks and that most of this 2400-m-thick section was deposited in a marine environment. We infer that this occurred in the late Paleocene or early Eocene. Coats (1956) provided evidence for a minimum thickness of about 600 m and speculated that the maximum is 4600 m. These observations suggest that the Finger Bay Volcanics is part of the initial series rocks, the Aleutian ridge basement complex (See Jake and White, 1969; Mitchell and Bell, 1973; Marlow and others, 1973.)

SOURCE OF SEDIMENT

The Finger Bay Volcanics was deposited and metamorphosed before deposition of the next recognizably younger strata, the Andrew Lake Formation. Probably by middle Eocene time, the growing Aleutian ridge had nearly reached sea level, and subaerial volcanoes contributed debris to surrounding basins. At times, the Finger Bay Volcanics may have contributed sediment to the Andrew Lake Formation, as clasts in some samples (samples 802–201, 802–202, table 1) are lithologically similar, but the overall amount of sediment derived from the Finger Bay Volcanics appears to be relatively small. The main source of Andrew Lake detritus was most likely contemporaneous volcanism. The host volcanic centers were eventually deeply eroded and perhaps in part covered by younger debris.

Because hydrothermal silicification of the Andrew Lake Formation was intense, it is difficult to identify the origin of the silica in the chert beds. It is not clear whether the silica in the chert-porcelanite section of the Andrew Lake Formation is released by the dissolution of siliceous biogenic debris, deposition from hydrothermal solutions, or both. Diatoms and minor radiolarians from the quartz chert occur in all states of preservation, from ghosts to specimens that retain frustule ornamentation. This suggests that at least part of the silica was derived from dissolution of siliceous microfossils. The calcite in this section is probably redeposited carbonate

released when foraminifers were replaced by quartz.

DEPOSITIONAL BASIN

The dimensions of the depositional basin of the Andrew Lake Formation are not known. Scholl and others (1970) speculated that the Andrew Lake strata accumulated in a fairly deep (500 m) basin along an early Tertiary Aleutian ridge. If the Yakak Peninsula strata (Wedge Point) are temporally equivalent to the Andrew Lake Formation, then they possibly represent the subaerial and shallow-marine facies of the deeper water Andrew Lake strata. The basin seems to have been no deeper than 500 m (fossils suggest 200–500 m), a situation very much like the present Aleutian Islands and the adjacent 200-m-deep Aleutian ridge platform. We infer that these rocks were deposited on the subaerial flanks of a volcanic complex and in adjacent offshore shelf and slope environments. The presence of a small enclosed basin, one isolated from turbidity-current deposition, is evident in the laminated chert and porcelanite of the Andrew Lake Formation.

ALTERATION OF SEDIMENTARY ROCKS

Burial diagenesis, local thermal metamorphism by dikes and sills, and hydrothermal activity contributed to the alteration of Eocene rocks. Burial diagenesis was an important process in the early stages of alteration of these rocks, primarily because they contain a large fraction of unstable mafic to intermediate volcanic rock fragments. Burial caused the transformation of the glassy parts of volcanic rock fragments to clays. These structurally weak rock fragments, upon further burial, decomposed to form a sedimentary rock consisting of framework grains of plagioclase, pyroxene, and rock fragments in a clay matrix. All the original glass shards and glass globules were altered or replaced during burial.

After uplift and some erosion, two additional stages of alteration strongly affected the character of the sedimentary rocks:

1. Numerous late Tertiary dikes and sills intruded and thermally metamorphosed adjacent wall-rock. Sedimentary rocks adjacent to dikes were baked, and locally epidote and prehnite formed. More commonly chlorite, hematite, quartz, and vermiculite mixed-layer clay phases formed next to dikes.
2. A more significant episode of alteration occurred in conjunction with the intrusion of Miocene plutonic rocks, when extensive formation of zeolites occurred.

Many observations favor hydrothermal fluids rather than zeolite-grade regional or burial metamorphism as the mechanism of alteration of the Andrew Lake and the Yakak Peninsula rocks:

1. At Andrew Lake, wairakite, the highest temperature zeolite, stratigraphically overlies laumontite and clinoptilolite, minerals characteristic of a relatively lower temperature metamorphic facies (Coombs, 1961; Harada, 1969; Seki and others, 1969).
2. Nonequilibrium mineral assemblages are common; for example, smectite is associated with laumontite. Low-temperature zeolites occur in close association with higher-temperature forms; for example, laumontite, clinoptilolite, and wairakite at Andrew Lake and laumontite, analcime, and yugawaralite at Wedge Point. (See Coombs and others, 1959; Seki, 1969; Kossovskaya, 1975.)
3. There is no apparent stratigraphic or spatial variation in the metamorphic grade of zeolites. The distribution of zeolites does not show zonal relations.
4. A wide variety of secondary minerals is associated with the zeolites.
5. Calcium zeolites (yugawaralite, laumontite, and wairakite) greatly predominate over sodium varieties (analcime; Kossovskaya, 1975).
6. Some crystals of quartz and laumontite are more than 2 cm long.

Less diagnostic but supporting evidence is that (1) ubiquitous quartz silicification suggests deposition from circulating hydrothermal fluids (Fournier, 1973; Coombs, and others, 1959), (2) mixed-layer clays, for example vermiculite-smectite-chlorite in our samples, commonly form in hydrothermal deposits (Bundy and Murray, 1959; Lovering and Shepard, 1960; Heystek, 1963; Steiner, 1968), (3) secondary mineral assemblages (except in the biogenic chert-porcelanite section) are independent of original rock type (Sigvaldason and White, 1961), and (4) reported occurrences of yugawaralite (and at most locations, wairakite) are from geothermal areas (Sakurai and Hayashi, 1952; Barrer and Marshall, 1965; Harada and others, 1969).

Hydrothermal solutions associated with emplacement of plutons and with the contemporaneous volcanic activity apparently permeated the Paleocene rocks and sealed any available pore space by deposition of secondary minerals. Rocks close to the main thoroughfares of circulating fluids were 50–75 percent replaced. Deposition of secondary minerals in

vesicles probably resulted from several different passes of hydrothermal solutions during which time the temperature decreased and the chemistry of fluids changed. Analysis for iron yielded 3.8, 5.6, and 6.8 weight percent Fe for samples 810-201, 810-301, and 811-201b, respectively, values that are similar to those found for mafic and intermediate volcanic rocks (Turner and Verhoogen, 1960). Circulating fluids apparently did not add much iron to the system; rather, the iron in the volcanic rocks was mobilized to form iron oxides and hydroxides, chlorite, celadonite, and stilpnomelane. Alteration of plagioclase and ferromagnesian minerals and ions from the circulating hydrothermal solutions provided abundant calcium for formation of laumontite, yugawaralite, wairakite, and minor calcite. Solutions were silica saturated with respect to quartz. Eberlein and others (1971) stated that the conditions for yugawaralite formation include low fluid pressure, 200-300°C, and alkaline solutions with silica saturated with respect to quartz.

REGIONAL TECTONICS

In recent years, there has been much speculation about what effect the subduction of an active oceanic ridge (spreading center) has on an island-arc complex (for example, Atwater, 1970; Grow and Atwater, 1970; Uyeda and Miyashiro, 1974; DeLong and Fox, 1977; DeLong and others, 1978). It has been proposed by some workers (Atwater, 1970; Hayes and Pitman, 1970; Marlow and others, 1973; among others) that subduction of a ridge will terminate ridge spreading. Uyeda and Miyashiro (1974) believed that spreading can continue long after subduction of the spreading center. They also suggested that widespread volcanism accompanies subduction of ridges. Grow and Atwater (1970) equated middle and late Tertiary orogeny in the Aleutian Islands and Alaska to subduction of the Kula ridge beneath the Aleutian-Alaskan part of the North American plate. DeLong and others (1978) speculated that regional greenschist-facies metamorphism in the Aleutian Islands resulted from subduction of the Kula ridge beneath the Aleutian island arc.

By the interpretation of Grow and Atwater (1970) and DeLong and others (1978), the Kula ridge entered the Aleutian trench between 20 and 35 m.y. ago (favored age is 30 m.y.). Our results, however, suggest that the 30-m.y. K-Ar ages on which DeLong and McDowell (1975) and DeLong and others (1978) base their conclusions are initial cooling ages of Aleutian island volcanic rocks and

not metamorphic ages. If ridge subduction produces an episode of regional lowgrade metamorphism, as DeLong and others speculate, then because the Andrew Lake and probably correlative sedimentary rocks on Adak Island are not regionally metamorphosed, subduction of the Kula ridge must have occurred before the late Eocene, about 50 m.y. ago. Models for North Pacific plate motion allow subduction of the Kula ridge at 50 m.y. or 35 m.y. ago depending on whether relative motions have been discontinuous or continuous, respectively (Cooper and others, 1976, fig. 4). Although the plate models are approximations, there is increasing evidence of discontinuous motion with faster rates of convergence in early Cenozoic time and slower rates during the middle and late Cenozoic; this evidence, then, favors subduction of the Kula ridge 50 m.y. ago (Hayes and Pitman, 1970; Hein, 1973; Hamilton, 1973; Scholl and others, 1977; also, see Francheteau and others, 1970; Larson and Pitman, 1972). Therefore, evidence for the timing and the effects of ridge subduction as proposed by DeLong and others (1978) can be interpreted variously. More likely, early Tertiary (Paleocene or Eocene) metamorphism resulted from the depositional burial and tectonic uplift of more than 4000 m of volcanic and sedimentary rocks. Emplacement of plutonic rocks at depth during early development of the arc complex may have contributed to the observed metamorphism.

CONCLUDING REMARKS

We suggest that sedimentary and volcanogenic rocks in the Wedge Point area are temporally equivalent to the upper Eocene, Andrew Lake Formation. However, despite the similarity in lithologic composition, degree of alteration, and induration, age-diagnostic fossils must be found in rocks in the Wedge Point area to justify including them as part of the Andrew Lake Formation. These rocks accumulated approximately 40 m.y. ago on the flanks of an active volcanic complex. Subaerial and marine (maximum 200-500 m deep) rocks are represented. Deposits underwent burial diagenesis that significantly reduced porosity and produced authigenic clay minerals, iron oxides, and possibly quartz. Additional alteration occurred in conjunction with intrusion of sills, dikes, and especially granodiorite plutons. Secondary minerals formed during these late-stage thermal and hydrothermal events are primarily zeolites (yugawaralite, laumontite, analcime, wairakite), clays, iron oxides, and quartz. Most pore spaces that remained after burial diagenesis were filled during this episode, essentially

eliminating any reservoir potential these strata may have had. Organic matter was either initially very low in these rocks, or if present was in places subsequently "cooked" by the heat of igneous intrusions. Consequently, these strata are unlikely sources of hydrocarbons.

The Finger Bay Volcanics was regionally metamorphosed to the greenschist facies some time before the late Eocene (possibly 50–55 m.y. ago). These rocks represent the oldest rocks exposed in the western Aleutian Islands. DeLong and McDowell (1975) and DeLong and others (1978) inferred from K-Ar ages that subduction of the Kula ridge spreading center resulted in a regional greenschist metamorphic event along the Aleutian arc about 35 m.y. ago (Oligocene). The absence of regional metamorphism in the Andrew Lake Formation suggests other interpretations. If Adak is typical of other Aleutian islands, either the Kula ridge was subducted about 50 m.y. ago or greenschist metamorphism need not accompany subduction of a spreading center.

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The Livengood Dome Chert, a New Ordovician Formation in Central Alaska, and Its Relevance to Displacement on the Tintina Fault

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and CLAIRE CARTER

SHORTER CONTRIBUTIONS TO STRATIGRAPHY AND
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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1126-F

*A newly defined formation provides a key to the
correlation of lower Paleozoic formations
and right-lateral movement on the
Tintina fault in east-central Alaska*



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THE LIVENGOOD DOME CHERT, A NEW ORDOVICIAN FORMATION IN CENTRAL ALASKA, AND ITS RELEVANCE TO DISPLACEMENT ON THE TINTINA FAULT

By ROBERT M. CHAPMAN, FLORENCE R. WEBER, MICHAEL CHURKIN, JR.,
and CLAIRE CARTER

ABSTRACT

The discovery of Late Ordovician graptolites in the Livengood Chert plus new data from field mapping and other paleontologic studies in the Livengood quadrangle necessitate major revisions in the Paleozoic stratigraphy in central Alaska. The term "Livengood Chert," pertaining to a formation consisting of chert, limestone, dolomite, shale, and argillite and originally assigned a Mississippian age, is abandoned. A predominantly chert formation, the Livengood Dome Chert, is herein newly defined and is dated by the graptolites as Late Ordovician. It is exposed in an east-northeast-trending belt about 91 km long in the Livengood quadrangle, and the type area is near Livengood Dome. Its structure is complex, and well-exposed thick sections are scarce; therefore the estimated thickness of 300–600 m is uncertain. The Livengood Dome Chert is overlain by an unnamed formation, composed largely of dolomite and limestone, that is provisionally assigned a Middle Silurian to Early Devonian age; the chert is underlain by Cambrian and Precambrian (?) argillite, slate, quartzite, siltstone, limestone, and chert. Extensive chert units similar to the Livengood Dome Chert in lithology and stratigraphic and structural position but paleontologically undated are present in the Tanana, Kantishna River, and Fairbanks quadrangles to the west and southwest. A chert unit that may be correlative with the Livengood Dome Chert crops out in the Circle quadrangle to the east. A correlation is suggested between the Livengood Dome Chert and the Ordovician part of the Road River Formation that lies farther east in the Charley River quadrangle. A correlation between the chert and other rock units of similar ages and lithologies in the Livengood and Charley River areas is significant to understanding the tectonics of the region because these areas are respectively south and north of the Tintina fault zone. The correlation implies about 300 km of right-lateral offset along this major fault system.

INTRODUCTION

Recent advances in the stratigraphic and paleontologic knowledge of Paleozoic rocks in central Alaska have provided data to allow revision of sev-

eral major rock units and their ages and to support significant new regional correlations and tectonic interpretations. A predominantly chert formation, the Livengood Dome Chert, is newly described in this report, and its age is identified as Late Ordovician on the basis of graptolites that were discovered in it in 1971. A formation consisting mainly of dolomite and limestone that immediately overlies the Livengood Dome Chert is also described but is not named. These formations formerly constituted the Livengood Chert that was described and assigned a Mississippian age by Mertie (1937, p. 105–111), and in this paper the term "Livengood Chert" is abandoned.

ACKNOWLEDGMENTS

The information presented here is largely the result of geologic mapping and studies in the Livengood quadrangle by several geologists between 1960 and 1971 (Chapman, Weber, and Taber, 1971). The discovery of graptolites by Donald M. Triplehorn, of the University of Alaska, Michael Churkin, Jr., and Claire Carter was a major contribution to this study (U.S. Geological Survey, 1972, p. A51–A52). Regional correlations and tectonic interpretations are based also on geologic work in the Charley River quadrangle (Brabb and Churkin, 1969) and the Tanana and Kantishna River quadrangles (Chapman, Yeend, Brosgé, and Reiser, 1975; Chapman, Yeend, and Patton, 1975).

We have benefited also from the geologic investigations in the Livengood area and the description of several chert thin sections by Robert L. Foster, from paleontologic and stratigraphic studies in the Livengood and White Mountains areas by J. Thomas

Dutro, Jr., and from geologic mapping by Donald Grybeck, who worked in the eastern part of Livengood quadrangle with Chapman and Weber in 1968. The geologic report on the Yukon-Tanana region, by Mertie (1937), who defined the major rock units and many of the geologic problems, was a most helpful base for the more recent work in the Livengood quadrangle.

ORIGINAL DESCRIPTION OF THE LIVENGOOD CHERT

The name Livengood Chert was first used in 1926 but without definition (Mertie, 1926, p. 79). However, Mertie had previously mapped and described this rock unit near Livengood, referring to it as "a stratigraphic series consisting dominantly of chert," and stated that the valley of Livengood Creek may be considered as its type locality (Mertie, 1918, p. 239-244). In 1937 the Livengood Chert was first defined, and it was described as extending "from a point north of the Sawtooth Mountains to the valley of Beaver Creek, north of the White Mountains, a distance of about 65 miles. The maximum width of this belt, in the vicinity of Livengood, is 8½ miles" (Mertie, 1937, p. 105). This belt is within the Livengood quadrangle. Mertie (1937, p. 105-111) identified an eastward extension of this formation in the hills "between the lower valleys of Beaver and Preacher Creeks" (Circle quadrangle) and "in a narrow belt crossing Woodchopper and Coal Creeks a short distance south of the Yukon River" (Charley River quadrangle). He also described westward extensions that occur as isolated beds in the vicinity of Sawtooth Mountain and as "metamorphosed equivalents of these rocks" in the Rampart district (Tanana quadrangle).

The lithology is dominantly chert, ranging in color from light smoky gray to black, and interbedded minor amounts of limestone, shale, and argillite (Mertie, 1937, p. 105-109). The limestone is commonly white to cream, crystalline, and in various stages of silicification and is less commonly dark gray, noncrystalline, thin bedded, and mostly un-silicified. Another rock type is chert conglomerate "composed essentially of chert pebbles in a matrix of chert" that "appears to lie at or near the base of the Livengood chert. Numerous small bodies of basaltic or diabasic greenstone are also found with the sedimentary rocks, but these igneous members are believed to be largely intrusive and therefore of later origin."

The rocks, according to Mertie, are closely folded, generally strike N. 60° E., and dip steeply south, forming a sequence overturned from south to north in which the same beds are probably repeated several times. Owing to the complex structure, no measurement of true thickness is possible, but "a considerable thickness of beds, perhaps several thousand feet," is estimated.

The Mississippian age determination was based on one fossil collection, 18AOF8 (Mertie, 1937, p. 110), from a limestone bed on a tributary of Lost Creek that contained crinoid stems *Batostomella* sp. and *Athyris* sp. This collection was accepted, with certain reservations, as of Carboniferous, probably Late Mississippian, age, although it lacked the more diagnostic Late Mississippian fossils that were found in collections of the undifferentiated Carboniferous rocks farther north in this region. Mertie states that "it is doubtful if this collection alone, considered without reference to others, even justifies a definite assignment to the Carboniferous," and " * * * the best estimate of the geologic age of the Livengood chert * * * is that it probably represents the base of the Carboniferous sequence in this region, and it is therefore classified as Mississippian."

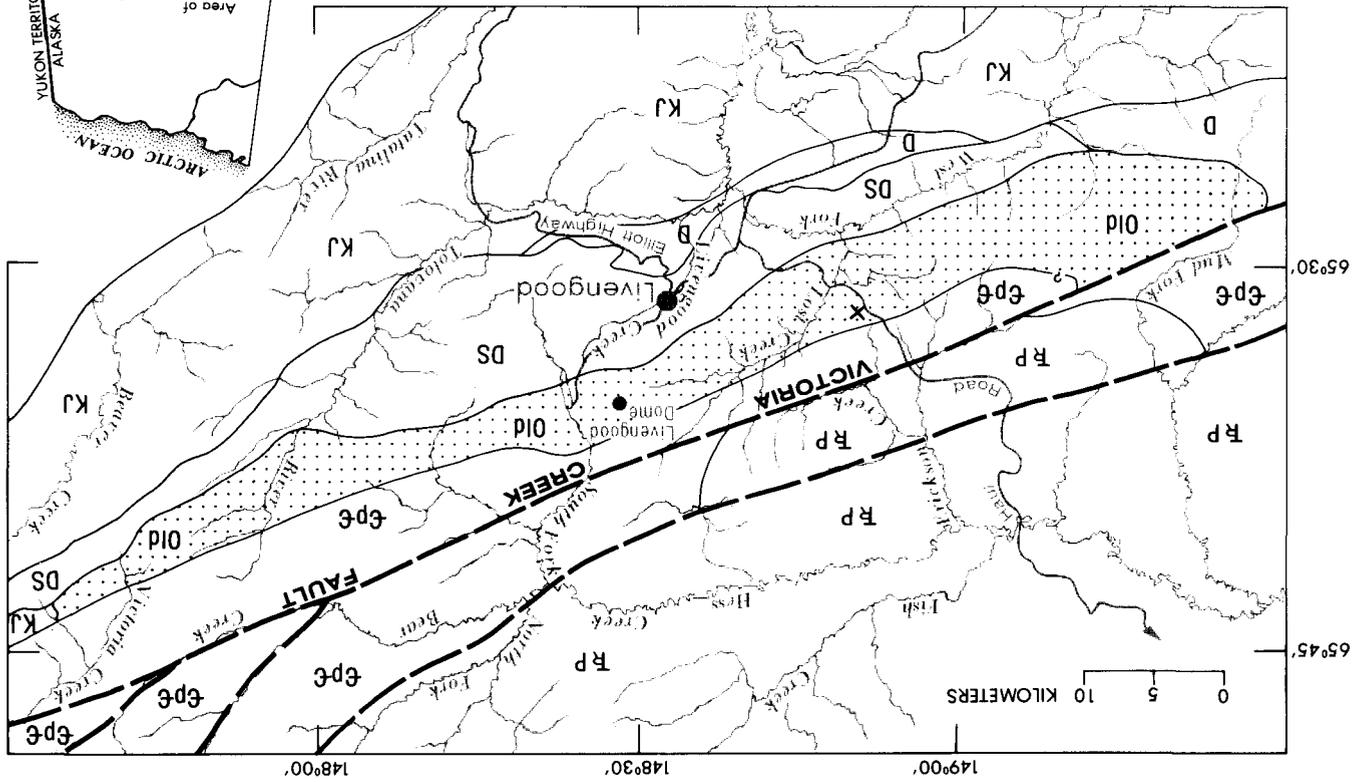
THE LIVENGOOD DOME CHERT

In recent geologic mapping prior to discovery of the Ordovician graptolites, Mertie's Livengood Chert was divided into two unnamed units, provisionally assigned an Ordovician to Devonian age: a lower unit that is predominantly chert and minor amounts of interbedded shale and some other rocks and an upper unit of predominantly limestone, dolomite, and minor amounts of chert and shale (Chapman, Weber, and Taber, 1971).

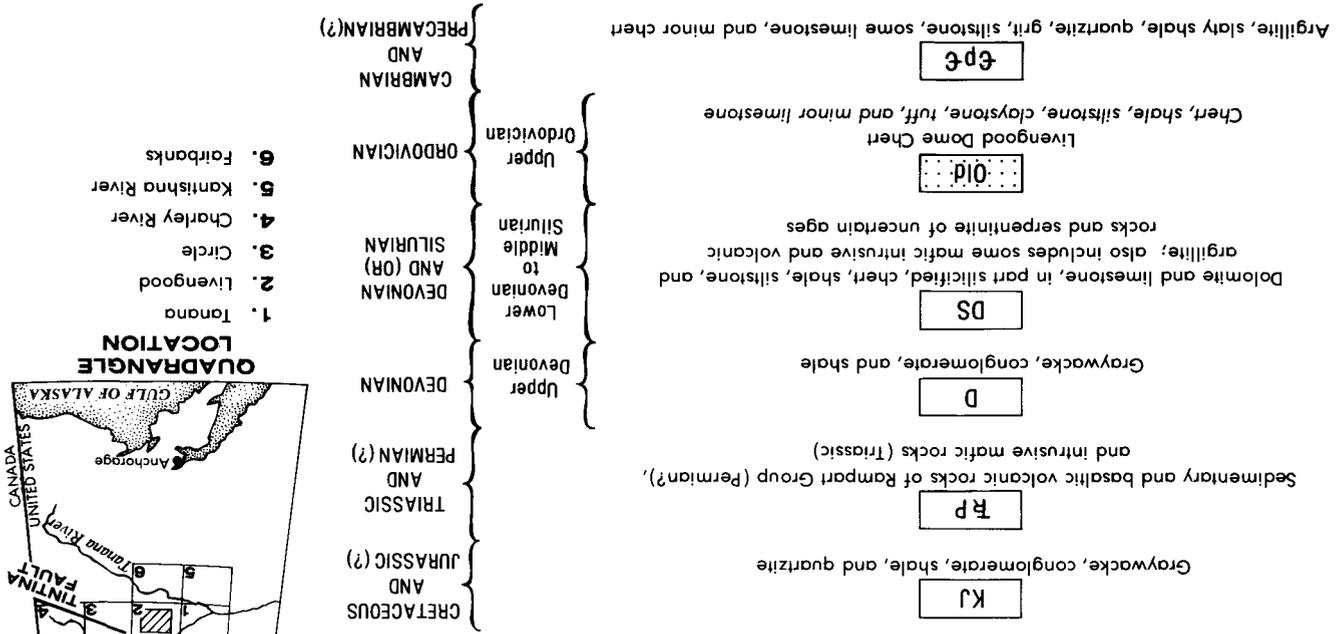
The lower, predominantly chert unit in the Livengood quadrangle that is now dated by the Ordovician graptolites is here named the Livengood Dome Chert. The upper, predominantly carbonate unit is here differentiated as a separate but unnamed formation. The term "Livengood Chert" as defined by Mertie is therefore abandoned.

AREAL DISTRIBUTION

The Livengood Dome Chert crops out in an east-northeast-trending belt (fig. 1) between the Mud Fork and the headwaters of Victoria Creek, a distance of about 91 km. The width of this belt generally is about 5 km but ranges from 1.6 to 9.6 km. Minor amounts of some other rocks, either unrecognized or too small to be shown at the map scale,



EXPLANATION



Site of Lost Creek borrow pit X

FIGURE 1.—Generalized bedrock geologic map of the central part of the Livengood quadrangle, showing the Livengood Dome Chert and other major rock units. Base from U.S. Geological Survey quadrangle, scale 1:250,000 (1956).

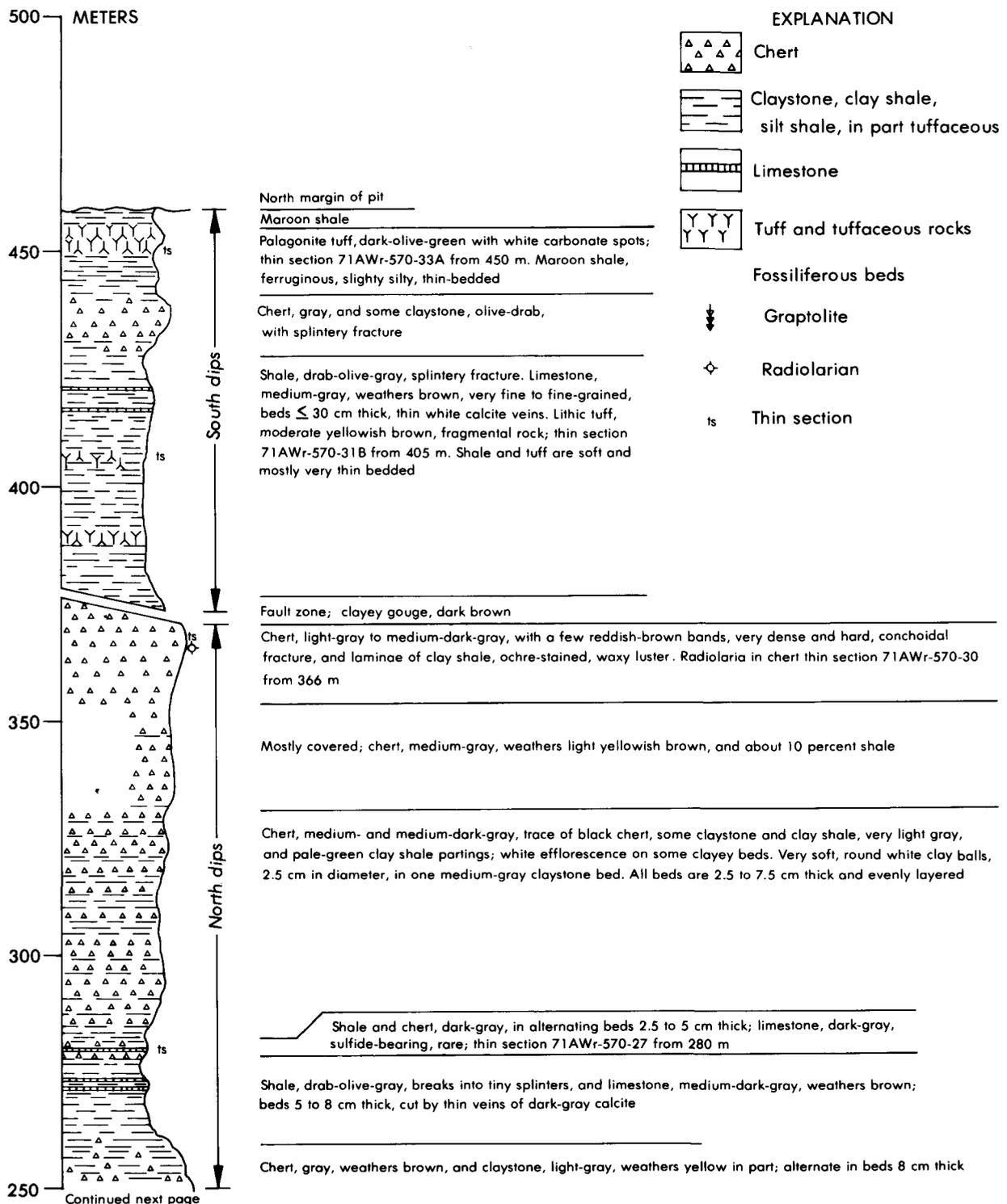
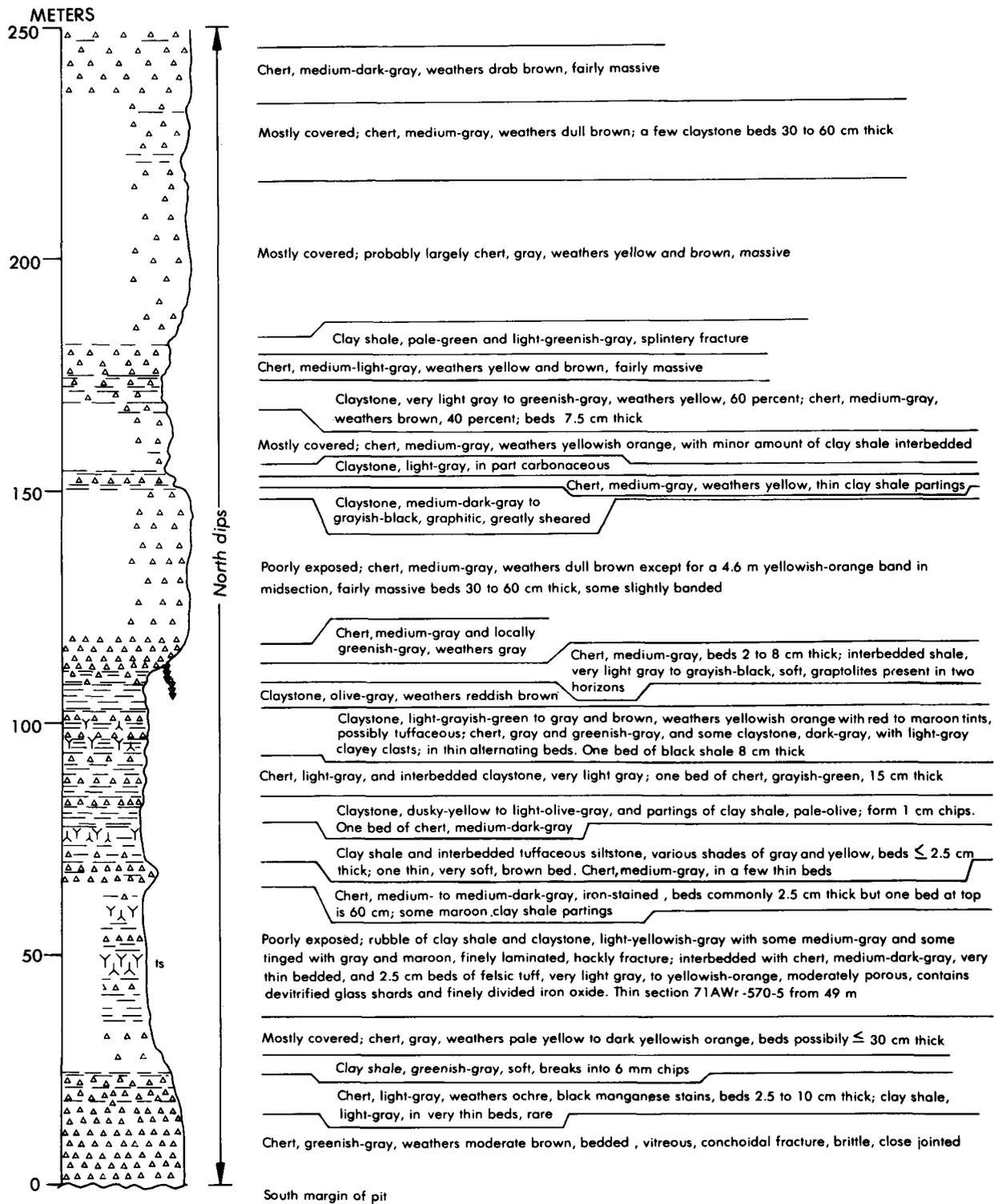


FIGURE 2.—Reference section of the Livengood Dome Chert in the Lost Creek borrow pit (see fig. 3 for location). The stratified. The amount and direction of movement on the fault are unknown,

are included. The exposures are such that a complete section and the exact lower contact could not be found, and the upper contact was seen at only one place. Within this belt the Livengood Dome Chert is best exposed in the area between the valleys of Lost Creek and the South Fork of Hess Creek,



graphic orientation and continuity of this section are uncertain because tops and bottoms of beds rarely could be determined and some beds may be repeated owing to undetected isoclinal folding.

which is herein designated its type area. The formation name is taken from Livengood Dome, which is underlain largely by this chert and is the most

prominent topographic feature in the type area. The thickest section, a reference section (fig. 2), was uncovered during 1970-71 in a large highway bor-

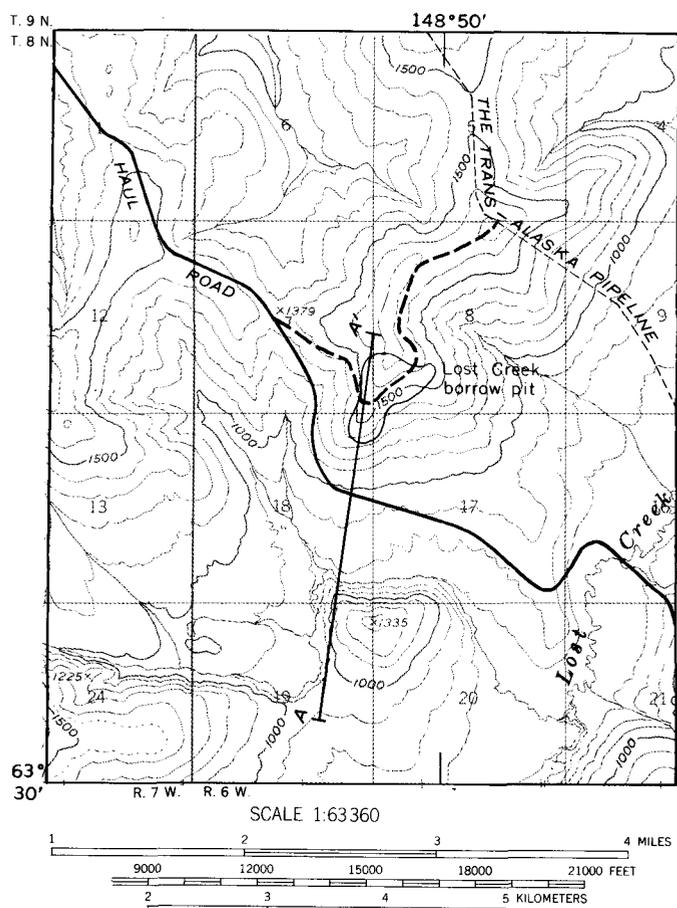


FIGURE 3.—Location of the Lost Creek borrow pit and cross section A-A' (fig. 4). Base from U.S. Geological Survey Livengood C-4 quadrangle, 1951.

row pit 13.6 km west of the town of Livengood and about 2.4 km west of Lost Creek in the SW $\frac{1}{4}$ sec. 8, T. 8 N., R. 6 W. (fig. 3).

West of the Mud Fork a belt of chert and meta-chert, apparently correlative with the Livengood Dome Chert, is present in the Tanana quadrangle (fig. 1) and extends over a distance of about 73.6 km between Hoosier Creek and Point Tilman on the Yukon River (Chapman, Yeend, Brosgé, and Reiser, 1975). An extensive, predominantly chert unit has been mapped in the northeastern and south-central part of the Kantishna River quadrangle (Chapman, Yeend, Brosgé, and Reiser, 1975; Chapman, Yeend, and Patton, 1975) and in the northwest corner of the Fairbanks quadrangle (Pévé and others, 1966). These cherts outside the Livengood quadrangle are tentatively correlated with the Livengood Dome Chert on the basis of lithologic similarities and stratigraphic and structural position. There is no definitive paleontologic evidence that these cherts

are all the same age. However, the recent discovery of radiolarians of probable early Paleozoic age in samples from both the Livengood Dome Chert and the chert in the south-central part of the Kantishna River quadrangle (D. L. Jones, oral commun., 1978) supports a general correlation of these two chert units.

To the east of Victoria Creek in the Circle quadrangle, the belt of chert mapped by Mertie (1937, pl. 1) between Beaver and Preacher Creeks was examined briefly by Churkin in 1968; no definitive age information was obtained here or in the immediately adjacent areas. Farther east, in the Charley River quadrangle, the Livengood Chert as mapped by Mertie in the Woodchopper and Coal Creeks area, on the north side of the Tintina fault, has been reinterpreted by Brabb and Churkin (1969) as two units: an argillite and chert unit of late Paleozoic age and the Step Conglomerate of Permian age. However, the Road River Formation (Churkin and Brabb, 1967; Brabb and Churkin, 1969) in the southeastern part of the Charley River quadrangle and also on the north side of the Tintina fault has, in part at least, the same age and lithology as the Livengood Dome Chert.

LITHOLOGY AND STRUCTURE

The Livengood Dome Chert in the type area consists of more than 50 percent chert that commonly ranges from light gray to grayish black, weathers to light and very light shades of gray, green, yellow, reddish brown, and red, and commonly has iron and manganiferous stains and thin coatings. Bedding, which in many outcrops is obscure, ranges from thick and massive (as much as 100 cm) to thin (2–8 cm) and includes some ribbon chert units; in part of the unit, banding accentuated by slight color differences is present. The chert and associated rocks are commonly jointed, irregularly fractured, and in places brecciated; thin to hairline white quartz veins are common along fractures and in places form a reticulated boxwork pattern.

Very thin layers and partings (a few millimeters to several centimeters thick) of clay shale, argillite, siliceous slaty shale, and siltstone are interbedded with chert, and there are uncommon thin units of tuff, tuffaceous siltstone, limestone, and possibly some graywacke. All these rocks, which form less than 50 percent of any chert section, range from light gray and olive gray to dark gray; included also are a few shaly beds that are grayish red to dark red and reddish brown and some pale-yellow to

yellowish-orange lithic tuffs. Because these rocks are thinner bedded and less resistant to weathering than the chert, they are poorly exposed or absent in natural outcrops and rubble patches, and our observations of them have been made chiefly in manmade cuts. A distinctive thin unit of small-pebble conglomerate, consisting of chert pebbles in a siliceous or chert cement, is present at several places near Livengood and Lost Creek. This chert pebble conglomerate apparently is in the lower part of the formation, but owing to complex structure and discontinuous outcrops, its stratigraphic position is uncertain.

In thin section the chert is cryptocrystalline but includes some microcrystalline quartz. In part it contains altered remnants of radiolarians (71AWr-570-30); some sponge spicules are also visible in hand specimens. Minor amounts of sericite and argillaceous grains are present. Hairline fractures filled with quartz, iron oxides, and mica are abundant. One section shows evidence of at least three sets of fractures and a granular quartz that has been invaded by silica. The deformation, fracturing, and rehealing of fractures are indicative of incipient or very low grade metamorphism.

A thin section of grayish-black siliceous siltstone, which is interbedded with chert in a borrow pit 6.4 km southwest of Livengood, shows the siltstone to be a moderately sheared and altered volcanoclastic rock containing quartz, much altered albitic plagioclase, colorless mica, chlorite, a zeolite (probably laumontite), and a large amount of what appears to be altered glass. The veinlets are largely quartz or zeolite plus quartz (J. W. Hawkins, written commun., 1966).

Tuff is interbedded with the chert in the Lost Creek borrow pit (fig. 2). A very light gray to pale yellowish-orange tuff (71AWr-570-5) in thin section shows cryptocrystalline to microcrystalline chert, probable devitrified glass shards, and some yellow, red, and brown earthy iron oxides and microcrystalline white mica; the tuff has a relict clastic or pyroclastic texture, and could be a water-laid sediment. Two other moderate yellowish-brown to dark-olive-green tuffaceous rocks (thin sections 71AWr-570-31B and -33A) are crystal to vitric tuff and vesicular palagonite tuff, which are generally less extensive and derived probably from basaltic or andesitic rocks.

Several medium-dark-gray limestones, in beds 5-8 cm in thickness and interbedded with shale and chert in the Lost Creek borrow pit, are calcarenites. A thin section (71AWr-570-27) shows about 85

percent interlocking sand-size carbonate grains that have been recrystallized and 15 percent iron oxides and sulfide that occur as tiny grains and fracture fillings.

Well-consolidated medium- to dark-gray and greenish-gray polymictic small-pebble conglomerates and conglomeratic volcanic graywackes noted in the area between Lost Creek and the headwaters of Erickson Creek are apparently interbedded in the Livengood Dome Chert. In thin sections, angular chert pebbles and grains are abundant, and angular pebbles and grains of quartz, feldspar, pyrobole, shale, and mafic volcanic rock are common in a very fine grained graywacke matrix.

The structure throughout the type area of the Livengood Dome Chert is complex; tight, isoclinal, and overturned folds, joints, irregular fractures, and faults of indeterminate magnitude are common. The regional strike is generally N. 60-70° E.; both south and north dips generally exceed 45°. The rocks throughout this area have been subjected to some degree of low-grade metamorphism, and the metamorphism appears to be controlled by the structural setting and relative competence of the rock type. Foliation is crudely formed in some of the weaker rocks.

An accurate thickness for this formation cannot be determined because of the structural complexity, absence of continuous exposures, and concealed upper and lower contacts. The reference section in the Lost Creek borrow pit has an apparent thickness of about 459 m, but because this section is cut by a fault of unknown displacement and includes dip reversals, it has a smaller and unknown true stratigraphic thickness. An estimated thickness of 300-600 m for the Livengood Dome Chert would be compatible with its relatively broad outcrop belt in the Livengood quadrangle and with similar size belts of probably correlative chert units in adjacent quadrangles.

The position of the upper contact of the Livengood Dome Chert can be mapped within narrow limits at many places in the outcrop belt, but the contact zone has been seen at only one site, on the north side of a hill 1.2 km south of the Lost Creek borrow pit (fig. 4). Here the section of rocks, all dipping 55°-65° S., consists of at least 9 m of greenish-gray to black, banded and thin-bedded chert overlain by about 60 m of medium-dark-gray thin-bedded chert wacke and interbedded silty shale, in which graded bedding indicates that this unit is in upright position. These rocks are in turn overlain by about 15 m of massive fine- to medium-grained sparsely fos-

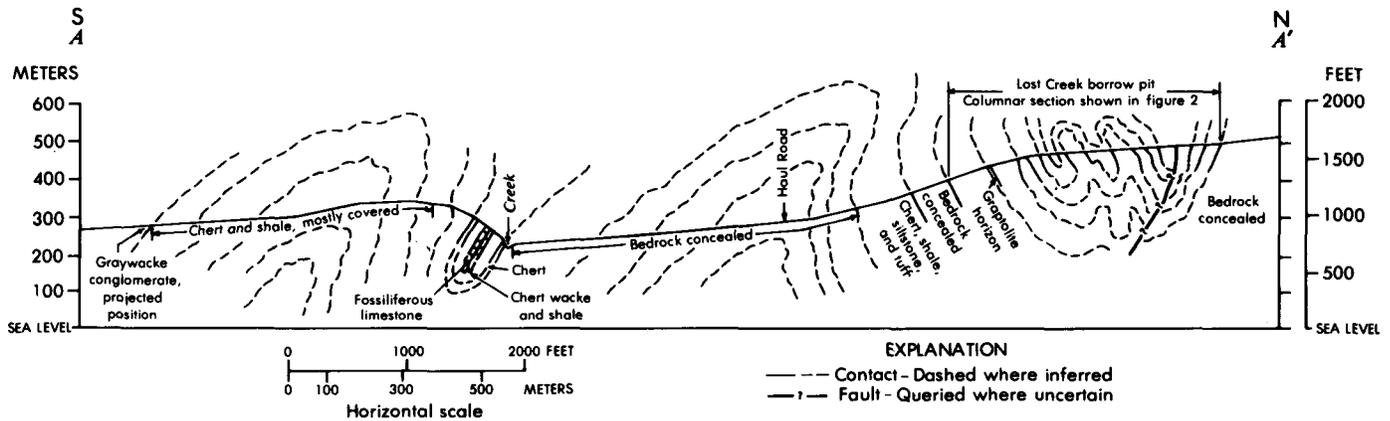


FIGURE 4.—Geologic cross section A-A' through the Lost Creek borrow pit, showing the structural interpretation. See figure 3 for location.

siliferous light-gray limestone, the basal 61 cm of which has thin lenticular beds containing some dark-gray rounded chert pebbles. The upper contact of the Livengood Dome Chert is placed immediately below the base of the limestone.

Where more fully represented in the Livengood quadrangle, the unnamed formation that overlies the Livengood Dome Chert is composed predominantly of very light gray to light-gray dolomite and limestone, is commonly slightly to nearly completely silicified, includes a minor amount of medium-dark-gray to black chert occurring as thin beds, lenses, and nodules and contains some thin beds of slaty shale, siliceous siltstone, and argillite. The uniformly dark color of this chert contrasts with the various shades of gray and other light colors that are characteristic of the chert in the Livengood Dome Chert. The other noncarbonate rocks in both formations are generally similar.

The exact age of this dominantly carbonate rock formation, shown as "dolomite and limestone" on figure 1, is uncertain. Based on exhaustive studies of the several small collections of fragmentary conodonts, corals, and brachiopods made in recent years and of collection 18AOF8 (Mertie, 1937, p. 110), the maximum age range of the fauna in the apparently basal unit is Middle Ordovician through Middle Devonian (Givetian). The conodont elements have a long range of Middle Ordovician to Middle Devonian (A. G. Epstein, written commun., 1976). The corals have a range of Silurian through Middle Devonian (W. A. Oliver, Jr., written commun., 1963). The brachiopods have a possible range of Middle Silurian through Early Devonian, but a Middle Silurian age is considered most reasonable by J. T. Dutro, Jr., (written commun., 1976). Therefore, an

age range of Middle Silurian to Early Devonian is provisionally assigned to this unnamed formation. Some mafic intrusive and volcanic rocks and serpentine are, for convenience in mapping, included with this formation. They are closely associated with the carbonate rocks and are considered to be of Silurian and (or) Devonian age; however, their exact ages and relations to the carbonate rocks are uncertain, and a discussion of these rocks is beyond the scope of this paper.

The lower contact of the Livengood Dome Chert has not been seen in the outcrop belt. It is, however, closely approximated within a zone of discontinuous outcrops and rubble patches along the northern margin of the outcrop belt. Older lower Paleozoic and Precambrian(?) rocks, including maroon and green argillite and slate, quartzite, siltstone, chert, and some limestone, lie immediately north of this contact zone but were not found in direct contact with identifiable Livengood Dome Chert. Near this contact zone, chert conglomerate and some chert breccia of uncertain origin occur in the Livengood Dome Chert. The nature of the contact is not clear, but we believe that it is unconformable and probably in part a fault contact.

REFERENCE SECTION IN THE LOST CREEK BORROW PIT

The thickest continuously exposed section of the Livengood Dome Chert known in the type area was examined in 1970 and 1971 in the Lost Creek borrow pit (figs. 2 and 3), which was opened in 1969-70 as a source of rock for construction of the Alyeska pipeline haul road north from Livengood. Subsequently this pit has been smoothed by bulldozing; in

1976 most of the bedrock section was not well exposed, and the graptolite beds were covered.

A section having an apparent stratigraphic thickness of about 459 m was measured across the floor of the pit from the lower, south edge to the north edge near the top of the hill. About 60 percent of the section is chert, and 40 percent includes thin beds of shale, claystone, siltstone, tuff, and tuffaceous rocks and a few thin beds of limestone. The beds strike about N. 70° E., dip 50°–70° N. in the southern part of the section, and dip about 70° S. in the north part of the section. Graded beds in one outcrop within the north-dipping part of the section suggest that these beds are overturned. Possibly all of the north-dipping section is overturned, but other evidence for this and for the orientation of the beds in the south-dipping part of the section was not found. A fault of unknown displacement, marked by a dark-brown clayey gouge zone, separates the north- and south-dipping parts of the section.

A detailed description of this section, including the positions of the graptolite horizon and thin-section specimens, is given in figure 2. A diagrammatic

cross section through the pit and continuing to the south to include a part of the unnamed limestone formation is shown in figure 4.

The true stratigraphic thickness represented in this section is not known because the bed orientation, dip reversals, and movement on the fault could not be accurately evaluated and because the section may be repeated by undetected isoclinal folding. Neither the chert conglomerate, which is probably characteristic of the lowest part of the Livengood Dome Chert, nor rocks of other formations above and below the Livengood Dome Chert were found in the pit. Therefore, this section is presumably representative of a part of the formation and does not include either of its contact zones.

PALEONTOLOGY

Graptolites were discovered in and collected (collection 71ACn-391) from thin shale beds interbedded with chert (fig. 5) in the Lost Creek borrow pit by D. M. Triplehorn, Claire Carter, and Michael Churkin, Jr., in 1971. Subsequently, an additional collection (71ACh-287, about 1.5 m above 71ACn-

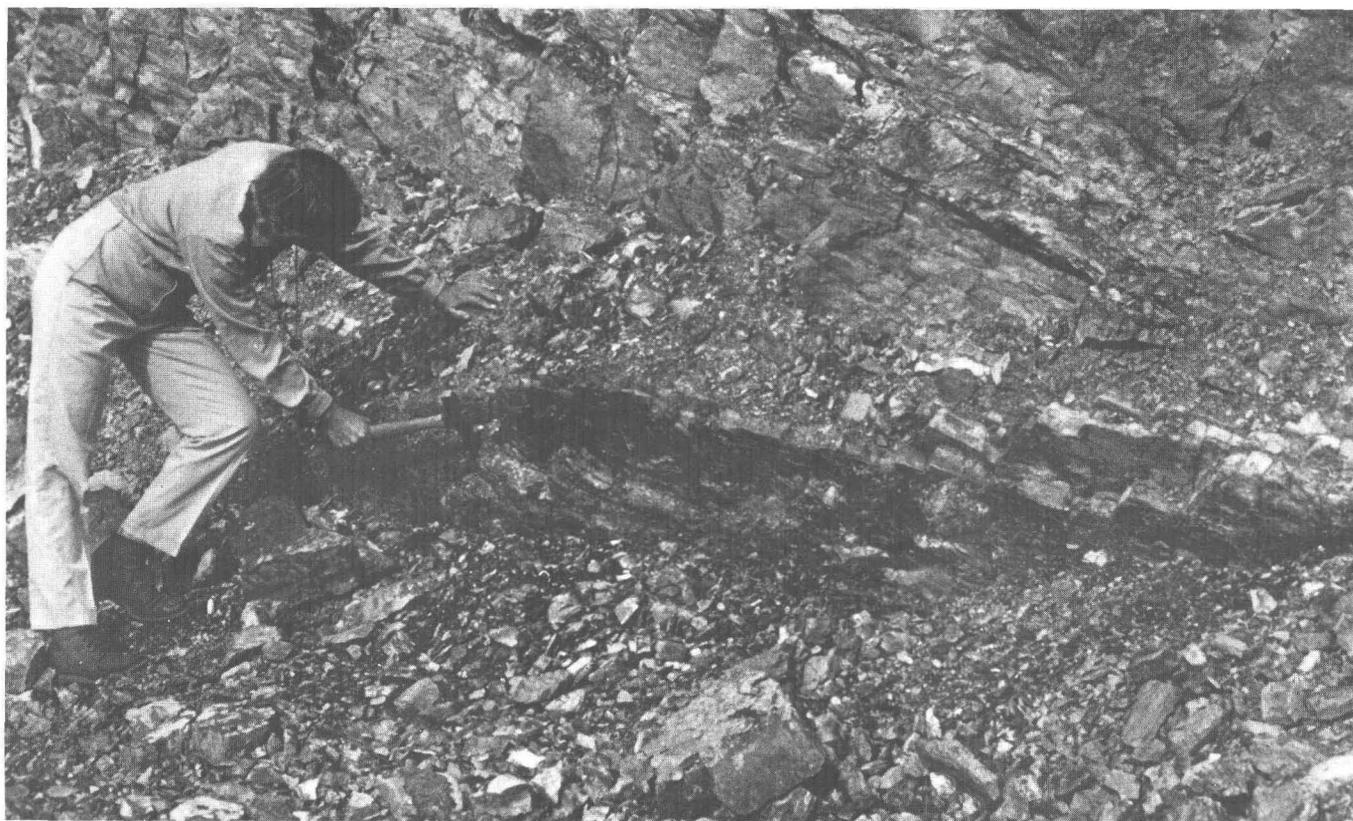


FIGURE 5.—Graptolite-bearing shale beds, indicated under the hammer, in the Livengood Dome Chert at the Lost Creek borrow pit.

391) was made from this site by others. Both collections of graptolites present problems in identification and age determination. The only genera present are of the biserial scandent type, a group that ranges in age from Middle Ordovician to Early Silurian. The usual variety of distinctively shaped genera that characterize most graptolite assemblages is unfortunately not found here.

Climacograptus aff. *C. longispinus supernus* Elles and Wood (fig. 6A) resembles *Climacograptus bicornis tridentatus* Lapworth in its three-spined proximal end, but it is narrower and differs also in the arrangement of its proximal thecae and spines. It resembles *C. l. supernus* in the arrangement of proximal thecae and lateral spines, but it has a much larger rhabdosome and also has an elongated virgella (middle spine), which *C. l. supernus* lacks. It is more than 57 mm long and 0.7–1.8 mm wide. *C. l. supernus* is an Upper Ordovician species from Great Britain (Elles and Wood, 1901–18, p. 196–197; Toghil, 1970, p. 22; Riva, 1974a, p. 120–125).

Climacograptus cf. *C. miserabilis* Elles and Wood (fig. 6D) is a small species measuring about 15 mm long and about 1 mm wide, having 14–10 thecae per centimeter. The thecal apertures are nearly opposite each other. The Alaskan form differs from *C. miserabilis* s.s. in the spacing of its thecae: *C. miserabilis* s.s. has 10–11 thecae per centimeter. *C. miserabilis* is found in Upper Ordovician and Lower Silurian rocks of Great Britain (Elles and Wood, 1901–18, p. 186–187). It also occurs in Upper Ordovician and Lower Silurian rocks of the Kolyma Basin in the northeastern U.S.S.R. (Koren' and Sobolevskaya, 1977).

Amplexograptus? pacificus pacificus (Ruedemann) (fig. 6H) is characterized by a short rhabdosome and double genicular spines (Riva, 1974b). The Alaskan specimen is about 19 mm long and 1.0–2.1 mm wide; it has 8 thecae in the proximal 5 mm and 13 thecae per centimeter distally. The genicular spines are about 0.5 mm long and occur in pairs on only a few thecae, perhaps owing to imperfect preservation. Most of the thecae are of the amplexograptid type, which has distinctly everted apertures and outwardly inclined supragenicular walls. T. N. Koren' (written commun., 1976) has found the Alaskan form to be no different from her specimens of *A.? p. pacificus* from the Kolyma region of the northeastern U.S.S.R. *A.? p. pacificus* is found in Upper Ordovician rocks in Idaho (Ruedemann, 1947, p. 429; Ross and Berry, 1963, p. 125; Riva, 1974b, p. 1457) and in the *Climacograptus supernus* Zone (= *Dicellograptus ornatus* Zone) of

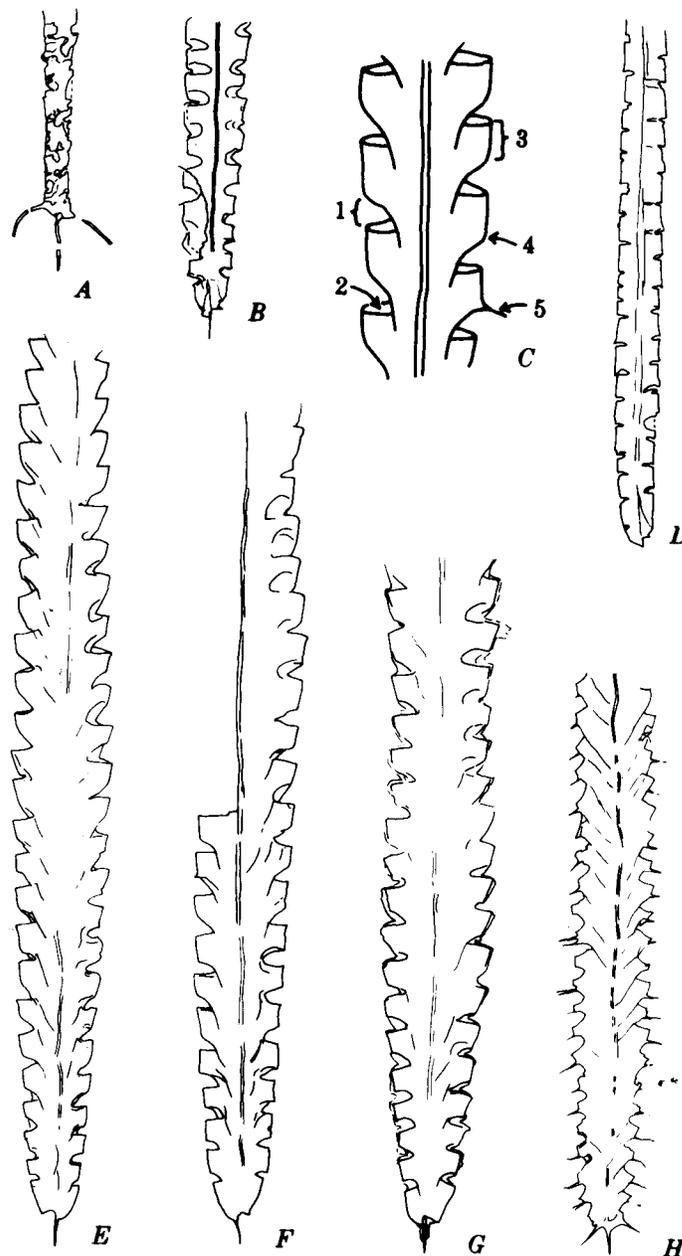


FIGURE 6.—Graptolites from the Livengood Dome Chert (all $\times 5$). A, *Climacograptus* aff. *C. longispinus supernus* Elles and Wood, USNM241051, collection 71ACh-287. B, *Climacograptus* sp., USNM241052, collection 71ACn-391. C, Diagram illustrating parts of thecae, as discussed in text: 1, apertural excavation, 2, thecal aperture, 3, supragenicular wall, 4, geniculum, 5, genicular spine. D, *Climacograptus* cf. *C. miserabilis* Elles and Wood, USNM241053, collection 71ACn-391. E, *Climacograptus* sp., USNM241054, collection 71ACn-391. F, *Climacograptus* sp., USNM241055, collection 71ACn-391. G, *Amplexograptus?* sp., USNM241056, collection 71ACn-391. H, *Amplexograptus? pacificus pacificus* (Ruedemann), USNM241057, collection 71ACh-287.

the Kolyma Basin and Kazakhstan, U.S.S.R. (Koren' and Soboleyskaya, 1977).

The specimen illustrated in figure 6G is questionably referred to the genus *Amplexograptus*. It is larger than other species of *Amplexograptus* (32 mm long, 1.3–3.0 mm wide, 12–10 thecae per centimeter) and differs in the details of the proximal end, but it possesses the outwardly inclined supra-genicular walls characteristic of the genus.

A few small climacograptids with genicular spines similar to those of *A. ? p. pacificus* occur in collection 71ACh-287. The remainder of both collections consists of numerous large- and medium-size climacograptids (figs. 6B, E, and F). Some of these may be transitional forms between previously described species, or they may be new species, but they lack any distinguishing features other than rhabdosome dimensions by which to identify them. Specimen F in figure 6 shows greatly retarded growth of one series of thecae. Only one other specimen having similar biserial-uniserial development was found, but it is a much wider form that has different thecal characteristics from the illustrated specimen. It is possible that this biserial-uniserial development may be due to injury, or it may be a prelude to the uniserial forms, such as *Monograptus*.

This fauna is Late Ordovician, even though it lacks the dicellograptids and distinctively spined species of *Climacograptus* that are characteristic of most Late Ordovician faunas of the Cordillera. This age assignment has been confirmed by John Riva (written commun., 1972) and W. B. N. Berry (oral commun., 1972). On the basis of our illustrations (fig. 6), Koren' (written commun., 1976) has correlated the Livengood Dome Chert fauna with faunas from the upper part of the Late Ordovician Zone of *C. supernus* (= *Dicellograptus ornatus* Zone) of the Kolyma Basin (Lukav beds) and Kazakhstan (Tchokpar horizon).

Nondiagnostic radiolarians and sponge spicules are the only other fossils that were known in the Livengood Dome Chert until early in 1978. Pending final determinations, radiolarians of probable early Paleozoic age have been identified by Brian Holdsworth and D. L. Jones in chert from the Lost Creek borrow pit and from the chert and slate unit of probable Ordovician age (Chapman, Yeend, and Patton, 1975) in the south-central part of the Kantishna River quadrangle (D. L. Jones, oral commun., 1978). Conodonts were looked for but not found in the shale interbedded with chert in and near the Lost Creek borrow pit.

REGIONAL CORRELATION OF ROCKS IN THE LIVENGOOD AND CHARLEY RIVER QUADRANGLES

The graptolites discovered in the Livengood Dome Chert indicate that it is coeval with part of the Road River Formation, a similar, but not identical unit that occurs much farther east in the Charley River quadrangle (Churkin and Brabb, 1965) and is widespread still farther east in Yukon Territory (Jackson and Lenz, 1962; Green, 1972). Much of the Livengood Dome Chert is pure chert that contains only minor shaly partings. The Road River, in contrast, is mainly graptolitic shale that has only a minor amount of siliceous shale and chert. The Livengood Dome Chert has some green tuff beds not found in the Road River Formation, and the Road River has a few conglomerate beds containing limestone and dolomite fragments that have not been recognized in the Livengood Dome Chert. The Road River in the Charley River area unconformably overlies a thick section of mainly limestone (Brabb, 1967) that in its upper part is rich in Cambrian trilobites (Palmer, 1968). The Road River underlies the McCann Hill Chert, a thin-bedded chert and siliceous shale unit that has a basal limestone unit rich in shelly fossils of Early Devonian age (Churkin and Brabb, 1965; Churkin and Brabb, 1967).

The fossiliferous Cambrian limestone and distinctive carbonate-rich formations of the Tindir Group of Precambrian age that occur below the Road River Formation are apparently absent in the Livengood quadrangle. Instead, the rocks structurally or stratigraphically below the Livengood Dome Chert along the north side of its outcrop belt are mainly siliceous. However, the presence of a thin fossiliferous limestone immediately overlying the chert, chert wacke, and silty shale of the Livengood Dome Chert suggests a correlation of this limestone with the basal limestone and shale member of the McCann Hill Chert. Certain other younger formations in the Livengood quadrangle also appear to have close correlatives in the Charley River area. For example, the coarse clastic rocks of Late Devonian age near Livengood may be a facies equivalent of the Nation River Formation; the volcanic and clastic rocks of the Rampart Group of probable Permian age may be related to the Circle Volcanics and associated clastic rocks of late Paleozoic age in the Charley River area; finally, the Lower Cretaceous Kandik Group of the Charley River area appears to have its counterpart in the Jurassic (?) and Cretaceous gray-wacke formations exposed in the Livengood and

Tanana quadrangles. Quartzites, unique to these Mesozoic sections in both the Livengood and Charley River areas, contain *Buchia*, which further strengthens this correlation.

TECTONIC SIGNIFICANCE

The tectonic significance of these stratigraphic correlations between the Livengood and Charley River areas is that the two areas of relatively unmetamorphosed Paleozoic strata occur on opposite sides of the Tintina fault zone. The Tintina fault in Alaska, where it crosses the Alaska-Yukon Territory boundary, separates greenschist, quartzite, phyllite, and greenstone of Paleozoic age on the south from essentially unmetamorphosed Precambrian, Paleozoic, and younger strata on its north side. This contrast in geology across the fault zone can be traced as far west as the western boundary of the Circle quadrangle, where the Tintina apparently splays into the several faults that are mapped in the northeastern part of the Livengood quadrangle (Chapman and others, 1971). On the south side of these faults near the eastern boundary of the Livengood quadrangle, unmetamorphosed rock sequences like those on the north side of the fault zone in the Charley River area first appear.

This geologic correlation strongly suggests a major right-lateral displacement along the Tintina fault system. The distance is about 300 km between the west end of the Road River Formation exposures near Nation in the Charley River quadrangle and the east end of the Livengood Dome Chert exposures near the head of Victoria Creek. Mainly on the basis of data from the Canadian part of the fault, Roddick (1967) estimated a 352- to 416-km displacement on the Tintina-Rocky Mountain trench system, and more recently, Tempelman-Kluit, Gordey, and Read (1976) suggested a displacement of 450 km.

A possible explanation for the differences in the calculated amounts of displacement is that the Tintina fault has splayed into several faults, and the total offset of an originally widespread unit, such as the Livengood Dome Chert, may be disguised by partial offset of detached, fault-bounded blocks of the unit within the fault system, for example: the Crazy Mountains, Little Crazy Mountains, and the hills between Preacher and Beaver Creeks, which are along the north boundary of the Tintina fault system in the northern part of the Circle quadrangle. Some of the more widespread rock units noted in this area in a brief reconnaissance by Churkin in

1968 are chert (probably part of the Livengood Dome Chert), chert-pebble conglomerate, basaltic rocks interlayered with chert (probably part of the Rampart Group), and interbedded quartzite, phyllite, and siltstone that in part contains *Oldhamia*, a fan-shaped trace fossil of either Cambrian or late Precambrian age. The structurally complex sequences of various rock types, apparently including both lower and upper Paleozoic units, that form these hills are tentatively interpreted, on the basis of limited field data and aeromagnetic data (U.S. Geological Survey, 1974), as parts of detached, fault-bounded blocks, or a block, within the Tintina fault system.

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