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GEOCHEMICAL STUDY OF SURFACE OIL SHOWS AND POTENTIAL SOURCE ROCKS IN THE ARCTIC NATIONAL WILDLIFE REFUGE (NORTH SLOPE ALASKA)

Donald E. Anders and Leslie B. Magoon

The presence of six oil seeps or oil-stained outcrops in the Arctic National Wildlife Refuge (ANWR) of northeastern Alaska indicates the possibility of commercial hydrocarbon occurrence in the subsurface. Interest in the resource potential of this region is heightened by the fact that ANWR is flanked by two important petroleum provinces, the Prudhoe Bay area on the west (estimated in-place reserves of 40–70 billion barrels of oil), and the McKenzie delta on the east (estimated in-place reserves of 740 million barrels). These productive areas adjacent to ANWR have quite different geology from each other, including different sources and geochemical character of their respective hydrocarbons. These differences make it impossible to extrapolate the geologic and geochemical relationships of the adjoining regions into the coastal plain of ANWR.

Organic carbon content, Rock-Eval pyrolysis, and vitrinite reflectance were used to evaluate the source rock quality and thermal maturity of five rock units within ANWR—the Shublik Formation, Kingak Shale, pebble shale, and bentonite and shale in the Colville Group. The average organic carbon content within these rock units is as follows: (1) 1.6 weight percent for the Triassic Shublik Formation; (2) 2.0 weight percent for the Jurassic and Lower Cretaceous Kingak Shale; (3) 3.0 weight percent for the Lower Cretaceous pebble shale; (4) 4.0 weight percent for the bentonite section of the Upper Cretaceous Colville Group; and (5) 2.0 weight percent for the Tertiary shale sequence and shale of the Upper Cretaceous Colville Group. The Cretaceous rock units in ANWR are thermally immature (vitrinite reflectance <0.5 percent) with respect to hydrocarbon generation on the coastal plain and thermally mature to overmature (vitrinite reflectance >1.0 percent) in the Sadlerochit and Shublik Mountains, where tectonic events have brought more deeply buried rocks to the surface. Rocks older than Cretaceous do not crop out in the coastal plain of ANWR and could not be evaluated. The oils collected from immature rocks in the coastal plain presumably migrated from a mature source.

In ANWR, organic matter type in the Tertiary section, the Lower Cretaceous pebble shale, and the Lower Cretaceous rocks of the upper unit of the Kingak Shale is predominantly type III (hydrogen index range 11–69 mg S_2/gC); whereas, the organic matter in the Lower Cretaceous bentonite-rich zone equivalent to part of the Colville Group is predominantly type II. The organic-matter type in the Jurassic unit of the lower Kingak Shale and the Triassic Shublik Formation could not be reliably determined because the only samples available for study (from the Sadlerochit and Shublik Mountains) are thermally overmature.

Based on comparison of the following geochemical attributes—stable carbon isotope ratios, tricyclic terpane ratios, pentacyclic:tricyclic terpane ratios, and saturate:aromatic hydrocarbon ratios, the ANWR oils can be divided into three genetic oil types, typified by (1) the oils from Augun Point, north and south Katakturuk River, and Jago River; (2) the oils from Manning Point; and (3) the oil from Kavik.

Oil-source rock correlation studies of carbon isotope ratios, tricyclic terpane ratios, and pen-

tacyclic:tricyclic terpane ratios suggest that the most promising source rock for the Augun Point, Katakturuk River, and Jago River oil types is the type II bentonite unit equivalent to part of the Colville Group. Geochemically, the Manning Point and Kavik oil types are sufficiently different than the bitumens extracted from the five rock units assessed in this study so as to suggest sources that have not yet been evaluated.

Given the foregoing similarity of the organic matter in the Colville Group bentonite to the oils from Jago River, Katakturuk River, and Augun Point, inference can be made that stratigraphic traps within the Colville Group, such as the fine-grained lenticular turbidite sands, may have some limited reservoir potential, but the thicker Tertiary fluvial and marine sandstone sequences of the delta facies may be more favorable exploration targets.

ADVANCES IN UNDERSTANDING NORTH SLOPE OIL AND GAS ACCUMULATIONS

K. J. Bird, L. B. Magoon, and C. M. Molenaar

The North Slope of Alaska petroleum province is an onshore-offshore region of complex geology covering an area of more than 100,000 mi^2 (260,000 km^2). Twenty-five oil and gas fields with in-place resources totaling more than 60 billion barrels of oil and 35 trillion cubic feet of gas have been discovered. Most North Slope oil and gas occur in a few large fields that are geographically concentrated within a relatively small area of the province, centered around Prudhoe Bay. The two producing fields, Prudhoe Bay and Kuparuk River, account for about 20 percent of daily United States oil production.

Petroleum prospective rocks on the North Slope consist of a Mississippian to Lower Cretaceous sequence derived from a northern provenance and a Lower Cretaceous to Holocene successor basin sequence derived from a southern provenance. These sequences are deformed along a foreland fold and thrust belt to the south and are relatively undeformed along a passive margin to the north. Volumes of oil are nearly equally distributed in reservoirs of these two sequences of rocks. Regional analysis indicates that the time of generation and the location of most North Slope oil and gas fields were controlled by Cretaceous and Tertiary tectonics and sedimentation.

Significant amounts of oil and gas are apparently yet to be discovered in this province, and most types of unconventional oil and gas resources are also present but as yet unevaluated; unconventional oil and gas resources include heavy oil or tar, oil shale, coalbed methane, tight gas sand, geopressured methane, and methane hydrates. Organic geochemical studies by industry and the USGS indicate that (1) two types of oil (and possibly several subtypes of each) are present, (2) Triassic and Jurassic source rocks are responsible for the most abundant oil type, and (3) Lower Cretaceous rocks are responsible for the other type—which accounts for only minor amounts of North Slope oil. In the coastal plain of the Arctic National Wildlife Refuge (ANWR), currently being evaluated, Triassic and Jurassic source rocks have probably been removed by Early Cretaceous erosion in much of the area. However, rich Lower and Upper Cretaceous source rocks, which are buried by as much as 4,000 m of Tertiary rocks in immediately adjacent areas, are more than adequate to generate significant amounts of oil in the ANWR, if the rocks are mature.

GAS HYDRATES, NORTH SLOPE OF ALASKA

T. S. Collett, K. J. Bird, L. B. Magoon, K. A. Kvenvolden, and G. E. Claypool

Gas hydrates are crystalline compounds of water and gas in which the solid water lattice accommodates the gas molecules in a cagelike structure, or clathrate. The formation of gas hydrates in well bores and pipelines has been recognized since the 1930's. Recently, naturally occurring gas hydrate deposits have been detected in many arctic regions of the world, including western Siberia, the Mackenzie Delta of Canada, and the North Slope of Alaska. Some may have future economic importance.

Direct evidence of gas hydrates on the North Slope comes from a gas-hydrate-saturated core, and indirect evidence has been obtained from drilling and open-hole geophysical logs that indicate the presence of a number of gas-hydrate-saturated stratigraphic horizons in the Kuparuk River oil field. Recently completed work conducted as part of the U.S. Geological Survey/Department of Energy cooperative gas hydrate research project has delineated a thick zone within which gas hydrates would be potentially stable on the North Slope. Methane gas hydrate stability mapping has been done, using data from stabilized well-bore temperature surveys, ice-bearing permafrost depths and temperature data collected during wire-line well logging. This mapping indicates that gas hydrates may be stable to depths as great as 1,300 m in the Prudhoe Bay area.

To evaluate the history of gas hydrate formation on the North Slope, the chemistry of the in-place hydrates must be examined. Geochemical analysis of rock samples provided by ARCO/ALASKA from two wells in the Kuparuk River oil field reveals a complex gas chemistry within the shallow gas-hydrate-bearing horizons, with methane being the primary gas constituent. Well-log evaluation has revealed that one stratigraphically controlled gas hydrate occurrence appears to be reservoired with a shallow heavy oil. The physical properties of the heavy oils may be influenced by the presence of gas hydrates; changes in the reservoir characteristics, such as decreased oil gravities, represent an engineering problem that must be dealt with before production of these oils.

A series of modifications of normal well-log evaluation procedures has enabled us to conduct several preliminary gas hydrate resource evaluations of selected gas-hydrate-bearing horizons on the North Slope. The identified in-place deposits of gas hydrates appear to be laterally continuous, suggesting that gas hydrates may be an unconventional source of natural gas.

CONODONT THERMAL MATURATION PATTERNS IN PALEOZOIC AND TRIASSIC ROCKS, NORTHERN ALASKA—GEOLOGIC AND EXPLORATION IMPLICATIONS

Anita G. Harris, I. L. Tailleur, and H. Richard Lane[2]

The Paleozoic through Jurassic stratigraphic sequence in the Brooks Range, northern Alaska, consists chiefly of platformal to intraplatform basin deposits 1–5 km thick. This comparatively thin sequence of heterogeneous lithologies was tectonically disrupted and shortened at least 600 km to form a stack of allochthons that were transported relatively northward and emplaced during earliest Cretaceous time. The Seward Peninsula appears to be a southwestern continuation of Brooks Range geology. Most of the western ⅕ of the Seward Peninsula contains 4–5 km of unmetamorphosed platformal, dominantly shallow water carbonate rocks of Early Ordovician through Devonian age. Eastward, these rocks are thrust onto a blueschist terrane of mafic volcanogenic and clastic deposits and mixed carbonate and clastic rocks of probable Ordovician through Silurian age. Adjacent to and possibly infolded with these rocks are metamorphosed shallow-water carbonates of Cambrian through Devonian age similar to the rocks of the western Seward Peninsula.

Cambrian through Triassic rocks make up at least 40 percent of the surface bedrock in northern Alaska, chiefly in the Brooks Range and Seward Peninsula. Thermal patterns in these rocks are based on conodont color alteration indices (CAI) from 2,000 collections representing 450 localities. These patterns show: (1) a gradual increase in thermal level from the northern margin of the Brooks Range to about ¾ of the distance across the range (from CAI 1 to 5.5 and above); (2) a belt of mixed high values (CAI 4.5 to 7) along the south border of the range; (3) thermal levels in surface and subsurface samples that are related to tectonic burial and not prethrust burial metamorphism, because CAI values in coeval rocks increase downward through the stack of allochthons; (4) the same CAI values in rocks above and below the Ellesmerian unconformity in the northeast Brooks Range; (5) an association of anomalously high CAI values with mineralized areas and plutonic rocks; and (6) a few anomalously high CAI areas of unknown origin that deserve geologic attention.

CAI mapping of northern Alaska shows that Cambrian through Devonian rocks in the geologically complex area of the western Seward Peninsula, along the northernmost edge of the western and central Brooks Range, and a very small area around the Yukon River at the Canadian border have thermal potential for hydrocarbons. In nearly all these areas, however, most of these rocks are beyond the thermal limit for oil. Areas that have thermal potential for both oil and gas in Mississippian through Triassic rocks include the subsurface of the north flank of the Colville basin, a 50-km-wide belt along the north flank of the Brooks Range as far east as the Philip Smith Mountains, and a small area around the Yukon River at the Canadian border.

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REGIONAL CORRELATION SECTIONS ACROSS THE NORTH SLOPE OF ALASKA

C. M. Molenaar, K. J. Bird, and T. S. Collett

Since the discovery of the giant Prudhoe Bay field in 1968 and the subsequent exploration in northern Alaska, new data have added immensely to the understanding of the stratigraphy of rocks underlying the North Slope coastal plain. The stratigraphic section consists of two sequences, the northern-derived Ellesmerian sequence and the overlying southern- and southwestern-derived Brookian sequence. The Ellesmerian sequence consists of (1) Mississippian through Triassic semistable platform carbonate and clastic rocks, zero to 2,500 m thick; (2) southward-prograding shelf to basinal Jurassic to earliest Cretaceous shales, zero to 1,100 m thick; and (3) less than 100 m of northward-transgressing Hauterivian-Barremian (Early Cretaceous) shale with a lenticular basal sandstone that unconformably overlies progressively older rocks to the north.

The Brookian sequence displays much greater time-transgressive facies relationships across the North Slope than does the Ellesmerian sequence. It is an easterly to northeasterly prograding wedge of Aptian(?) (Lower Cretaceous) through Tertiary clastic rocks as much as 4,000 m thick. In ascending order, this sequence consists of (1) less than 300 m of Aptian(?) to Maestrichtian basinal shale and bentonite, the lower part of which is generally organic rich; (2) as much as 3,000 m of Albian to Eocene basin-slope or prodelta shale with turbidites in the lower part; and (3) as much as 2,400 m of Albian to Quaternary shallow marine and nonmarine deltaic and alluvial-plain sandstone, shale, and conglomerate. A network of regional well-correlation sections across the North Slope, based in part on micropaleontologic and seismic data, shows that these different facies of the Brookian sequence are coeval with each other across depositional strike, and that most of the nomenclature established in the western North Slope is not applicable to the eastern North Slope.

ACCRETION, SUBDUCTION, AND UNDERPLATING IN SOUTHERN ALASKA—INITIAL RESULTS FROM THE TRANS-ALASKA CRUSTAL TRANSECT

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The Trans-Alaska Crustal Transect (TACT) is a major U.S. Geological Survey project aimed at determining the structure and evolution of the Alaskan crust along a north-south corridor paralleling the trans-Alaska pipeline and extending offshore across the Pacific and Arctic continental margins. Begun in the summer of 1984, TACT work to mid-1985 has incorporated geologic mapping, petrologic and geochronologic studies, seismic refraction/wide-angle reflection profiling, and gravity and magnetic investigations. Vertical reflection profiling and magnetotelluric sounding will begin in 1986. The transect was launched in the Chugach Mountains and Copper River Basin in southern Alaska; over the next 5 years it will proceed northward to Prudhoe Bay and across the continental margins.

In the first two seasons, TACT investigations focused on three abutting accreted terranes and the underlying shallow lithosphere. From south the north, the terranes are (1) the Prince William terrane (PWT), composed of an accreted Paleocene and Eocene deep-sea fan complex, oceanic volcanic rocks, and pelagic sediments; (2) the Chugach terrane (CGT), composed of accreted Upper Cretaceous flysch and oceanic basaltic rocks, accreted and subducted(?) Upper Jurassic to Lower Cretaceous sheared melange, and subducted(?) Lower(?) Jurassic or older blueschist/greenschist; and (3) the composite Wrangellia/Peninsular terrane (WRT/PET), consisting primarily of upper Paleozoic andesitic arc rocks with associated mafic and ultramafic plutonic rocks, an overlying Triassic sedimentary and volcanic sequence, and superposed intrusive and extrusive magmatic rocks of the Jurassic Talkeetna arc.

The PWT is thrust relatively northward beneath the CGT along the Contact fault system, and the CGT is thrust at least 40 km northward beneath the WRT/PET along the Border Ranges fault system. At the southern margin of both the CGT and WRT/PET, shallow high-velocity bodies (depths $\gtrsim$2–3 km and 1 km; V_p=6.8–7.1 km/s and 6.1–6.4 km/s, respectively) characterized by magnetic and gravity highs reflect uplift of mafic and ultramafic basement along these thrusts. The Border Ranges fault system apparently soles into a subhorizontal low-velocity layer of uncertain origin flooring the northern CGT and the southern WRT/PET at about 7–9 km depth. The Contact fault system may sole into a deeper, gently north dipping low-velocity layer at about 9–12 km. Three additional north-dipping low-velocity layers are defined between about 15 and 35 km depth beneath the CGT. We interpret the four dipping low-velocity layers and the subjacent high-velocity (V_p=7.8–8.3 km/s) layers as subducted assemblages of oceanic crust and mantle rocks. Based on the occurrence of earthquakes in the lower two assemblages, we infer that active subduction involves the lower two assemblages and that the upper two have been underplated onto the continental plate.

THE SHUBLIK FORMATION—A MODEL FOR DEPOSITION IN AN ANCIENT MARINE UPWELLING ZONE

Judith Totman Parrish

The Shublik Formation (Triassic, North Slope of Alaska) comprises several lithologic facies that are consistent with deposition in an upwelling zone. These include the following: (1) black, laminated, pyritic limestone; (2) nodular and oolitic phosphorite; and (3) glauconitic sandstone and siltstone. The facies are distributed in east-west-trending belts, with the limestone facies farthest to the south (basinward) and the glauconitic facies farthest to the north (shoreward), where it occurs only in the subsurface. This distribution also is reflected in the vertical succession. Although the facies intertongue, the limestone and glauconite are never interbedded with each other, but both can be interbedded with the phosphorite.

Rocks in the limestone facies contain as much as 6 percent total organic carbon. The high organic carbon content, paucity of bioturbation, presence of pyrite grains and nodules, and relative enrichment in such elements as cobalt, copper, and nickel all suggest that the rocks in this facies were deposited in an anoxic environment. Furthermore, the limestone facies is fossiliferous, containing extremely abundant, very thin shells of pelagic bivalves. The abundance of these shells is evidence for high biologic productivity in the water column overlying the anoxic sediments. Phosphate in the adjacent facies (as much as 14 percent P in the nodules) supports this interpretation. Phosphate indicates a high rate of supply of phosphorus-rich organic matter to the sediment-water interface; in modern upwelling zones, the phosphate is mobilized from the organic matter in the anoxic zone and reprecipitated at the zone's edges. Glauconite in the third facies is indicative of slightly reducing conditions. Glauconite occurs as filling in microfossil tests, glauconitized fecal pellets, grain coatings, and cement. The former two types of grains can result from micro-reducing environments, but the latter two types suggest a reducing environment in the sediment as a whole. Therefore, the lithological and geochemical facies of the Shublik Formation are congruent with a depositional environment in which high biologic productivity created an oxygenation gradient from anoxic in the most highly productive part to slightly dysoxic closer to the shoreline. This interpretation is most consistent with the conditions and sediments found in modern upwelling deposits.

NANUSHUK GROUP COAL INVESTIGATIONS—NORTH SLOPE OF ALASKA

E. G. Sable, G. D. Stricker, and R. H. Affolter

The North Slope of Alaska contains vast resources of virtually undeveloped coal, much of which occurs within mineable depths. The main coal-bearing units, the Corwin and Chandler Formations of the Lower and Upper Cretaceous Nanushuk Group, underlie more than 25,000 mi^2 (64,750 km^2) of the North Slope. They contain low-sulfur, low-ash, subbituminous, and coking-quality bituminous coal in gently dipping beds as thick as 20 ft (6.1 m), within stratigraphic intervals as thick as 10,000 ft (3,050 m). Coal resources of lesser quality and quantity also occur in other Upper Cretaceous, Lower Mississippian, and Tertiary rocks.

The river-dominated, in part coeval, Corwin and Umiat deltas controlled the distribution of Nanushuk Group coal-forming environments. The larger Corwin delta (Corwin Formation), in the western part of the North Slope, prograded northeastward and eastward; the smaller Umiat delta (Chandler Formation), in the central part, prograded northward. Most organic deposits formed on delta plains; others formed in alluvial-plain or delta-front environments. Most North Slope coal beds are lenticular and irregular, probably due to accumulation in interdistributary basins, infilled bays, or inland flood basins. Some widespread tabular beds that formed on wide, slowly sinking delta lobes may also be present. The major controls of coal rank and degree of deformation were depth of burial and subsequent tectonism.

Since 1975, ninety-six coal samples from the Corwin and Chandler Formations have been analyzed in order to evaluate coal quality and element distribution. Their apparent rank ranges from lignite A in undeformed strata to high-volatile A bituminous in moderately deformed units.

Coal from the North Slope is significantly lower in ash, volatile matter, O, Si, Al, Ca, Fe, Ti, Cu, F, Li, Mn, Mo, Pb, Sb, Se, Th, and Zn than Cretaceous coal of the western conterminous United States. Sulfur values are as low as 0.1 percent, and elements that normally show a positive correlation with sulfur are also low. Variations in element content probably reflect geochemical differences in the Corwin and Umiat delta systems.

Nanushuk Group hypothetical coal resources on the North Slope are estimated to be 3.1 trillion short tons. This value is the sum of 1.8 trillion tons of near-surface (<500 ft (150 m) of overburden) bituminous coal, 1.24 trillion tons of near-surface subbituminous coal to lignite A, and 0.06 trillion tons of more deeply buried subbituminous coal. Of the total, roughly 2.53 trillion tons of coal occurs in beds having less than 15° dip. These estimates indicate that the North Slope of Alaska may contain as much as one-third of the United States coal resources.

Information about North Slope coal is scant compared to major coal-producing areas in the conterminous United States: the Powder River Basin, for example, contains more than 5,000 test wells, whereas North Slope coal information is available from less than 50 test wells. A systematic drilling program is needed to develop more accurate resource estimates and increase the currently sparse and mostly localized information on quality and geochemistry of North Slope coals.

GEOCHEMICAL CHARACTERIZATION OF SELECTED COALS FROM THE BELUGA ENERGY RESOURCE AREA, SOUTH-CENTRAL ALASKA: SITE OF A PROPOSED COAL MINE

Gary D. Stricker, Ronald H. Affolter, and Michael E. Brownfield

The Tertiary Kenai Group of the upper Cook Inlet region, south-central Alaska, is a nonmarine sedimentary sequence, as thick as 8,000 m. It consists, in ascending order, of the Hemlock Conglomerate, Tyonek Formation, Beluga Formation, and Sterling Formation. All the units are coal bearing, but the thickest beds are found in the Tyonek Formation of early Oligocene to middle Miocene age. This formation is a 1,160- to 2,750-m-thick sequence of massive sandstones, siltstones, and claystones with interbeds of thick coal and a minor number of tuffs(?) and tonsteins. The Tyonek Formation is believed to have accumulated in poorly drained alluvial lowlands adjacent to tectonically active highlands containing sporadically active volcanoes.

The Beluga energy resource area is approximately 90 km west of Anchorage in the upper Cook Inlet region. This area contains over 1 billion short tons of coal resources in the Tyonek Formation alone. The area is tentatively scheduled for coal production beginning in the early 1990's. For baseline data 43 samples representing eight coal beds (Capps, Waterfall, M, O, Q, and three unnamed beds), were analyzed from four U.S. Geological Survey drill holes. Statistical summaries of proximate and ultimate analyses, heat-of-combustion, forms-of-sulfur, and 40 major, minor, and trace elements were compiled and evaluated, along with the mineralogy of the low-temperature ash for each sample. Analyses show an apparent coal rank that ranges from subbituminous B to subbituminous C, with a variable ash content of 4.7 to 46.5 percent. Total sulfur ranges from 0.08 to 0.33 percent, one of the lowest reported total sulfur ranges for any United States coal.

Concentrations of Si, Al, K, Ti, Be, Cr, Cu, F, Ga, La, Li, Sc, Th, U, V, Y, Yb, and Zr show a variation in concentration that is directly related to the ash content of the coal; linear correlation coefficients are greater than 0.8. The M bed has the lowest ash content as well as the lowest concentration of ash correlated elements, whereas the Capps coal bed has a relatively higher ash content and therefore, a higher concentration of these elements. The variability of ash content is probably a direct result of the proximity of the original peat swamp to nearby tectonically active highlands and the episodic nature and varying composition of the adjacent highland's volcanic eruptions.

Mineral analysis of the low-temperature ash reveals a predominance of kaolinite with minor mica-type clays and a varying amount of quartz. X-ray diffraction of selected coal samples indicates the presence of the hydrated alumino-phosphate mineral goyazite ($SrAl_3(PO_4)(OH_5) \cdot H_2O$), which is the strontium end member of the solid-solution plumbogummite series. The presence of this mineral is further supported by chemical analyses of the whole coal, which indicate unusually high concentrations of strontium (1,430 ppm) and phosphorus (4,100 ppm). Previous studies of the minerals of the plumbogummite series report the minerals occurring in altered nonmarine tuffs, which suggests that goyazite in the Tyonek Formation coals probably formed during early diagenesis of air-fall volcanic ash that landed in the peat accumulating swamps.

POTENTIAL GAS GENERATION IN SUBDUCTED SEDIMENTS OF THE EASTERN ALEUTIAN TRENCH AREA

Roland von Huene

Sediment being subducted in the eastern Aleutian Trench has a potential to generate large volumes of gas, even though the content of organic carbon in the sediment is low, averaging about 0.4 percent. This high potential for gas generation results primarily from the enormous volume of sediment undergoing subduction. Along the eastern Aleutian Arc-Trench system, an average 3-km-thick sheet of sediment is being subducted at the rate of about 60 km per million years. The geothermal gradient in this region is generally 30°C/km, based on one series of measurements in a deep well and on the depth of the base of the gas-hydrate zone. Such a gradient suggests a temperature regime in which the maximum gas generation in the subducting sediment occurs beneath the upper slope. Thus the sediment of the upper slope, as opposed to that of the shelf, could be the most prospective for gas accumulation if suitable migration paths and reservoirs are present.