Lithological, Geotechnical Properties Analysis, and Geophysical Log Interpretation of U.S. Geological Survey Drill Holes 1C–79, 2C–80, CW 81–2, and CE 82–1, Tyonek Formation, Upper Cook Inlet Region, Alaska

U.S. GEOLOGICAL SURVEY BULLETIN 1835

Prepared in cooperation with the State of Alaska
Department of Natural Resources

U.S. DEPARTMENT OF THE INTERIOR
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By JACK K. ODUM, LYNN A. YEHLE, HENRY R. SCHMOLL, CYNTHIA A. GARDNER, and LARRY L. DEARBORN

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

For readers who wish to convert measurements from the metric system of units to U.S. customary units, the conversion factors are listed below.

Metric unit	Multiply by	To obtain U.S. customary unit
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square centimeter (cm^2)	0.1550	square inch ($in.^2$)
gram (g)	0.035	ounce (oz)
meganewton per square meter (MN/m^2).	145	pounds per square inch (psi)
megapascal (MPa)	145	pounds per square inch (psi)

Lithological, Geotechnical Properties Analysis, and Geophysical Log Interpretation of U.S. Geological Survey Drill Holes 1C–79, 2C–80, CW 81–2, and CE 82–1, Tyonek Formation, Upper Cook Inlet Region, Alaska

By Jack K. Odum, Lynn A. Yehle, Henry R. Schmoll, Cynthia A. Gardner, *and* Larry L. Dearborn[1]

Abstract

The Tyonek Formation of early Oligocene through middle Miocene age is composed of nonmarine sequences of sandstone, siltstone, claystone, carbonaceous claystone, and subbituminous coal and lignite, all probably deposited in a poorly drained alluvial basin environment. Four continuously cored drill holes penetrated this coal-bearing formation to obtain lithologic, geotechnical, and geophysical information that would be useful in evaluating the stability of natural and manmade slopes, ground response to seismic activity, blasting effects, equipment selection for excavation, ground-water conditions, and erosion and weathering potential of both spoil piles and in-situ geologic materials. Drill holes USGS 1C–79 (121 m deep) and USGS 2C–80 (61 m deep) were drilled in the Capps coal field, approximately 100 km west northwest of Anchorage, Alaska. Drill holes CW 81–2 (102 m deep) and CE 82–1 (115 m deep) were drilled in the Chuitna coal field, approximately 80 km west of Anchorage. Analyses of lithologic abundances and stratigraphic unit characteristics indicate that the Capps coal field strata are probably representative of a basin margin setting, whereas the Chuitna coal field strata were deposited in a more midbasin position, that is, in an environment of finer grained sediments.

Test-result ranges of slake-durability index, point-load-strength index, laboratory unconfined compressive strength, and ultrasonic velocities differ widely for specific lithologies. However, on the basis of computed means, lithologies within a drill hole or coal field area can be arranged in the following order of increasing strength and durability: noncemented and weakly lithified sandstone, siltstone, claystone, carbonaceous claystone, and coal. An arrangement of lithologies into three groups is probably more realistic. The noncemented and weakly lithified sandstone, in most cases, can be considered to have almost zero unconfined compressive strength and durability. Siltstone, claystone, and carbonaceous claystone all have low-to-moderate strength and durability depending on clay-particle content and size, orientation, and quantity of micaceous and carbonaceous lamina and stringers. Coal units have unconfined strengths of at least twice those of the other, fine-grained lithologies. Local carbonate-cemented sandstone lenses have unconfined compressive strengths much higher than coal. However, these lenses are rare in occurrence and are not generally included in comparison discussions of the other major lithologies. Overall, the strength classification in terms of hardness for the majority of the lithologies of the Tyonek Formation is from stiff soil to soft rock.

[1]State of Alaska Department of Natural Resources.

INTRODUCTION

This report summarizes the results of field and laboratory measurements on core from drill holes USGS 1C–79, 2C–80, CW 81–2, and CE 82–1, located in the upper Cook Inlet region of south-central Alaska (fig. 1). The general objective of the Energy Lands Program in Alaska, of which this study is a part, is to provide information that would lead to a better understanding of the nature and extent of the engineering and environmental geology concerns in areas of potential coal and other development in the Beluga resource area of the upper Cook Inlet region, Alaska. This report contains lithologic, geotechnical, and geophysical information that is needed to evaluate and predict the response of the coal-bearing Tyonek Formation to large-scale mining and related development in the Capps and Chuitna coal fields. Specifically, the information may be used to evaluate the stability of natural and manmade cut slopes, ground response to seismic activity, blasting effects, equipment

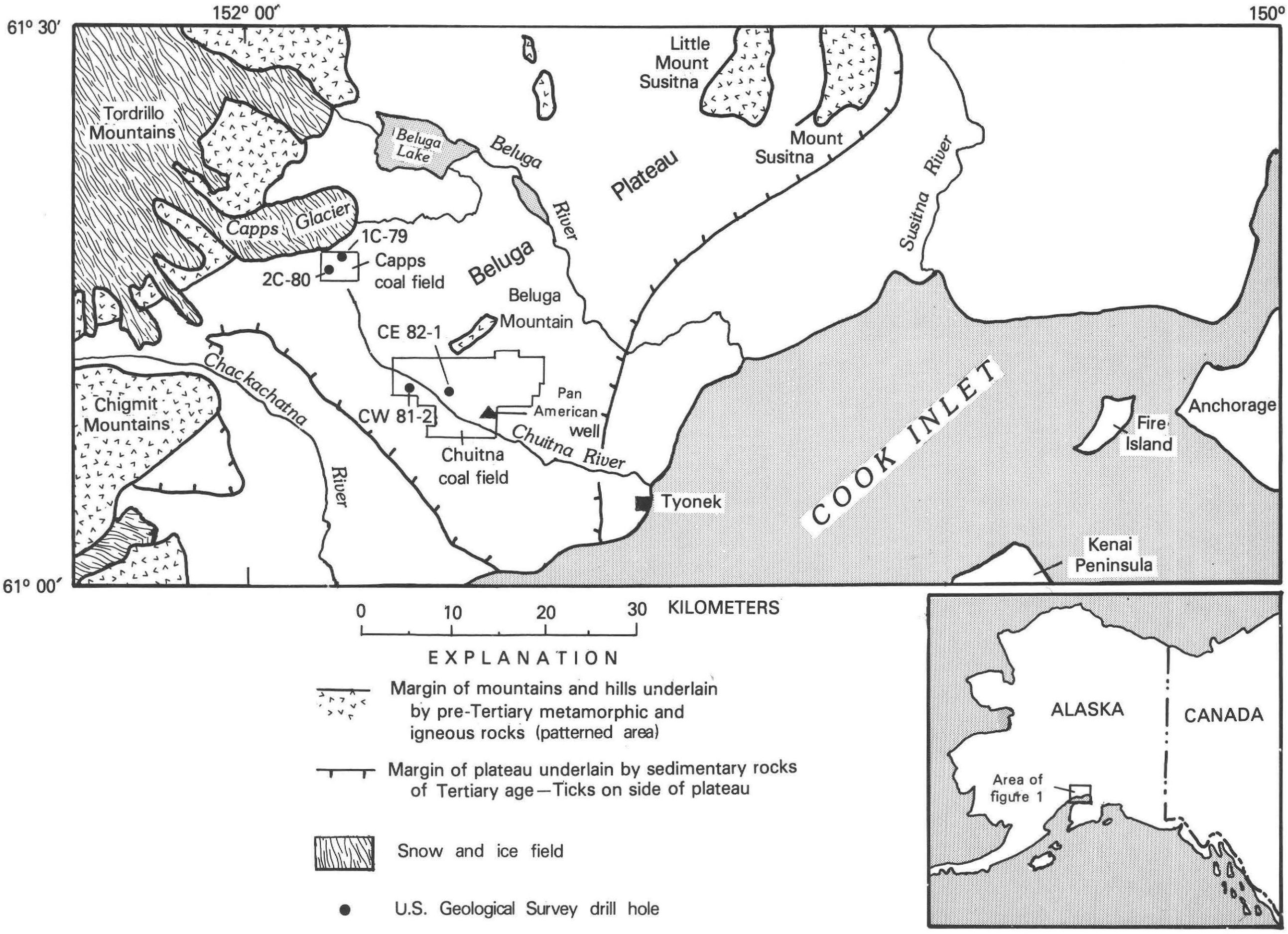

Figure 1. Index map showing the location of the four U.S. Geological Survey drill holes in the Capps and Chuitna coal fields, in the upper Cook Inlet region, Alaska.

selection for excavation, ground-water conditions, and erosion and weathering potential of spoil piles and in-situ geologic materials.

Acknowledgments

Thanks are given to the many individuals and organizations that provided help toward our efforts to gather data on the geologic units of the Tyonek Formation. Drilling and sample recovery was accomplished by Exploration Supply and Equipment Co., Anchorage, Alaska. Beluga Coal Co. of Placer U.S., Inc., San Francisco, Calif., and Diamond (Shamrock) Alaska Coal Co., Anchorage, provided geologic field data. Field assistance and sample analysis and testing were provided by the U.S. Geological Survey, Denver, Colo. Special thanks are given to A.D. Pasch, Anchorage Community College, Anchorage, and B.A. Carpenter, formerly of the Alaska Division of Geological and Geophysical Surveys, Anchorage, for well-timed geologic help in the field.

DRILL HOLE LOCATION

Two principal coal fields are present west of Anchorage, Alaska (fig. 1): The Capps field is approximately 100 km to the west-northwest of Anchorage, and the Chuitna field is 80 km to the west. In the Capps field, two holes were drilled. Drill hole USGS 1C–79, which is 121 m deep, is situated on a relatively flat upland surface (fig. 1). The site, located at NE¼ sec. 23, T. 14 N., R. 14 W., Tyonek B–5 quadrangle, Alaska, is approximately 100 km west of Anchorage and 38 km northwest of Cook Inlet (fig.1). Drill hole USGS 2C–80, which is 61 m deep, is located at NE¼ sec. 26, T. 14 N., R. 14 W., Tyonek B–5 quadrangle, Alaska, approximately 1.3 km southwest of drill hole USGS 1C–79. Stratigraphic correlation of the Waterfall coal bed between both drill holes indicates that the lower two-thirds of drill hole USGS 2C–80 lies stratigraphically below the bottom of hole USGS 1C–79. Core from both holes is believed to be representative of the lower part of the Tyonek Formation of early Oligocene through middle Miocene age

(Wolfe and Tanai, 1980). Preliminary lithologic observations, field-test data, and geophysical log interpretation for these two drill holes were reported by Chleborad and others (1980, 1982). Detailed lithologic logs and the results of field and laboratory geotechnical tests for these two drill holes were reported by Odum (1986).

Two holes were also drilled in the Chuitna coal field. Drill hole USGS CW 81-2, which is 102 m deep, is situated on the edge of a small, gently sloping basin that drains northwestward into the Chuitna River. The site is located on the west side of the Chuitna River at SE¼NW¼ sec. 33, T. 13 N., R. 13 W., Tyonek A-5 quadrangle, Alaska, approximately 90 km west of Anchorage. Drill hole USGS CE 82-1, which is 115 m deep, is situated on a north-trending interfluve between branches of a tributary to Chuit Creek, about 5.6 km north of its confluence with the Chuitna River. The site, located at SW¼SW¼ sec. 24, T. 13 N., R. 13 W., Tyonek A-5 quadrangle, Alaska, is approximately 104 km west of Anchorage and 29.7 km northwest of Tyonek, a native village on the northwest side of Cook Inlet (fig. 1). Strata from these two holes are believed to be representative of probably the middle to upper part of the Tyonek Formation. However, because of local faulting, folding, and limited surface exposures in the area, the exact stratigraphic relationship between the two holes is not certain. The Chuitna coal bed of Barnes (1966), which crops out for 13.7 km along the Chuitna River canyon, is correlated with the stratigraphically highest coal bed in the Pan American well (Calderwood and Fackler, 1972; fig. 1) and is also considered to correspond with the named brown coal bed in the Chuitna coal field, east of the Chuitna River, in the terminology of Ramsey (1981). Five other coal beds have been recognized beneath the brown coal bed, and in stratigraphically descending order, they are: the yellow, green, blue, orange, and red coal beds (Ramsey, 1981). This report refers to the two major coal beds in drill hole USGS CE 82-1, as the upper and lower beds, which may correlate (B.J.G. Patch, Placer U.S., Inc., San Francisco, Calif., written commun., 1981) with the green and blue coal beds, respectively, of Ramsey (1981). Coal bed terminology ("M", "O", and "Q") used in stratigraphy in drill hole USGS CW 81-2 (fig. 5*C*) is adapted from B.J.G. Patch, Placer U.S., Inc., San Francisco, Calif. (written commun., 1981). Preliminary field-test data and geophysical log interpretation for drill holes USGS CW 81-2 and USGS CE 82-1 were reported by Odum and others (1983, 1986). Detailed lithologic logs and the results of field and laboratory geotechnical tests for these two drill holes were reported by Odum (1986).

FIELD AND LABORATORY PROCEDURES

All four drill holes were continuously cored using an HQ-sized rotary-wireline core system (6.35-cm-core diameter). The core was retrieved, logged, and preserved as follows: Core contained in the split-barrel samplers was transferred at the drill rig to the logging team. Drilling information, such as drilling rate, depths of core intervals, percent of recovery, nature of drilling fluids, and hydrologic conditions, was recorded.

The core was photographed on color film using both instantaneous-development and 35-mm single-lens reflex cameras. Included in each photograph was a card identifying the core-run number, depth interval, and an appropriate page from the rock-color chart of Goddard and others (1970) for color comparison and identification. Information on discontinuities, color, laminations, hardness, and degree of weathering was recorded.

Point-load-strength-index and moisture-content measurements were performed on selected samples to provide a base of field data to compare with subsequent laboratory tests. To test "soft" samples having unconfined compressive strengths of less than 0.44 MPa, a pocket-penetrometer strength tester (Soiltest, Inc., 1978) was used. For material of greater strength, a point-load tester was used following the procedures described by Brock and Franklin (1972) and the ISRM (1972a). The presence of carbonate cement was determined by applying diluted (15 percent) hydrochloric acid to the core at selected intervals.

Untested core was wrapped in cheesecloth, labeled, coated with polycrystalline wax, and placed in cardboard boxes that were padded with split styrene inserts to minimize disturbance during transport to the U.S. Geological Survey Engineering Geology laboratory, Golden, Colo. To avoid hydrocarbon contamination, core samples containing coal strata were not waxed, but sealed in plastic sleeves.

Soon after the completion of drilling, continuous natural gamma radiation, gamma-gamma radiation, neutron radiation, hole diameter, spontaneous potential, single-point resistance, and temperature measurements were obtained. Logging procedures followed the techniques described by Keys and MacCary (1971).

Upon arrival at the U.S. Geological Survey laboratory, the core samples were stored in a controlled high-humidity environment. Samples selected for geotechnical and physical properties testing were prepared and tested according to the American Standards for Testing and Materials (ASTM) procedures. Index tests were performed according to the procedures developed by the originating authors. Previously published field point-load-strength-index and moisture-content values, along with new laboratory data, are presented in the various figures and tables in this report.

GEOLOGIC SETTING

Physiography and Surficial Geology

The Capps and Chuitna coal fields are situated on the Beluga plateau (Schmoll and Yehle, 1978; fig. 1), which is one of the higher lying physiographic subdivisions of upper Cook Inlet basin and is characterized by a relatively thin cover of Quaternary deposits. The Quaternary deposits are mainly glacial in origin and Pleistocene in age and overlie Tertiary bedrock (Schmoll and others, 1984). The eastern and southwestern borders of the plateau are marked by prominent escarpments that descend to the Susitna lowland and the Chakachatna-McArthur embayment, respectively; in these low-lying areas the Tertiary rocks are buried more deeply by Pleistocene and Holocene deposits that are mainly of estuarine origin. The Beluga plateau rises gently in elevation from 50-m-high coastal bluffs that border Cook Inlet along its southern margin to elevations of about 1,000 m to the northwest at the margin of the Tordrillo Mountains which rise abruptly to peaks as high as 4,000 m. Lower hills and mountains, including Mount Susitna and Beluga Mountain, interrupt the continuity of the plateau and rise to elevations of about 500 m.

The glacial deposits that cover the Beluga plateau have been mapped by Yehle, Schmoll, and Chleborad (1983a, b), Yehle, Schmoll, and Gardner (1983), and Schmoll and Yehle (1987). Deposits have been subdivided mainly on the basis of a series of prominent end and lateral moraines that were deposited in a complex, interwoven pattern by glaciers of different ages and sources (Schmoll and Yehle, 1986). The positions of these moraines, as well as major areas of other surficial deposits, are shown with respect to the locations of the four drill holes on figure 2. The end and lateral moraines are characterized by variably hummocky terrain and generally thicker deposits of glacial diamicton (till), whereas the areas of ground moraine are more gently rolling to nearly flat and have thinner glacial diamicton. Outwash channels and plains, which are commonly covered by gravel that may be only a thin veneer and are generally too small to show at the scale of figure 2, are found within and adjacent to the margins of most of the moraines.

Numerous landslide deposits occur within and on the escarpments that border the plateau, but only the largest of these deposits are shown on figure 2. Other surficial deposits include a variety of volcaniclastic debris flows.

The plateau is drained principally by the Beluga and Chuitna Rivers and their tributaries, which are incised 15–75 m beneath the plateau surface and flow in narrow, steep-walled valleys. Most of the valley walls are thinly veneered by colluvium that conceals the Tertiary bedrock in many places, but exposures of bedrock are common along the major river-valley walls and are present locally in the valley bottoms where Holocene alluvium on low terraces is generally thin.

Tertiary Bedrock

The Tertiary sedimentary rocks of the upper Cook Inlet basin are continental in origin and comprise forearc-basin deposits of both early and late Cenozoic tectonic cycles (Fisher and Magoon, 1978). Surface exposures in the Beluga area were described in detail by Barnes (1966), whose work emphasized the coal deposits. The Tertiary rocks throughout the basin had been collectively called the Kenai Formation, primarily on the basis of subsurface data that were compiled during exploration for oil and gas. The Kenai Formation was later raised to group rank and divided into five formations (Calderwood and Fackler, 1972). In ascending order, these formations are the West Foreland, Hemlock, Tyonek, Beluga, and Sterling. Subsequently, the West Foreland Formation was excluded from the Kenai Group by Magoon and others (1976).

The Tyonek Formation underlies the area of the Capps coal field, as well as most of the Beluga area to the southeast. It is early Oligocene through middle Miocene in age; outcrops near Capps Glacier and along the Chuitna River serve as the type section for the Seldovian Stage (Wolfe and others, 1966; Wolfe, 1977). The type section of the formation, in a well south of Tyonek village, is 2,331 m thick and includes at least 15 thick coal bed sequences (Calderwood and Fackler, 1972). Only a small part of the formation is exposed, including two principle coal beds, and the stratigraphic thickness of these exposed beds is not well known (Schmoll and others, 1981). Strata exposed in the Chuitna River area are believed to belong to the upper part of the Tyonek Formation; this interpretation is supported by a published radiometric age of about 15.8 Ma from a volcanic ash that was taken from one of the coal beds along the Chuitna River (Turner and others, 1980, p. 95).

LITHOLOGIC DESCRIPTION OF CORED STRATA OF THE TYONEK FORMATION

Depositional Environment Model

The Tyonek Formation is composed of nonmarine units of sandstone, siltstone, claystone, carbonaceous claystone, and subbituminous coal and lignite, all probably deposited in a poorly drained, alluvial-basin environment. Hite's (1976) depositional model (fig. 3) depicts a basinward merging of coarse-grained alluvial fans that were situated along tectonically active basin margins, with finer grained alluvial and flood-plain deposits near the center of the basin. Excellent settings for peat accumulation are found in flood plains: sag ponds along faults, sloughs and abandoned channels, and poorly drained regions between coalescing fans (Hite, 1976).

The Capps coal field is situated near the margin of what Hackett (1977) termed the Beluga basin, whereas the Chuitna coal field is located in what is thought to be a more midbasin position, that is, in an environment of finer grained sediments. Figure 4, a photograph of the

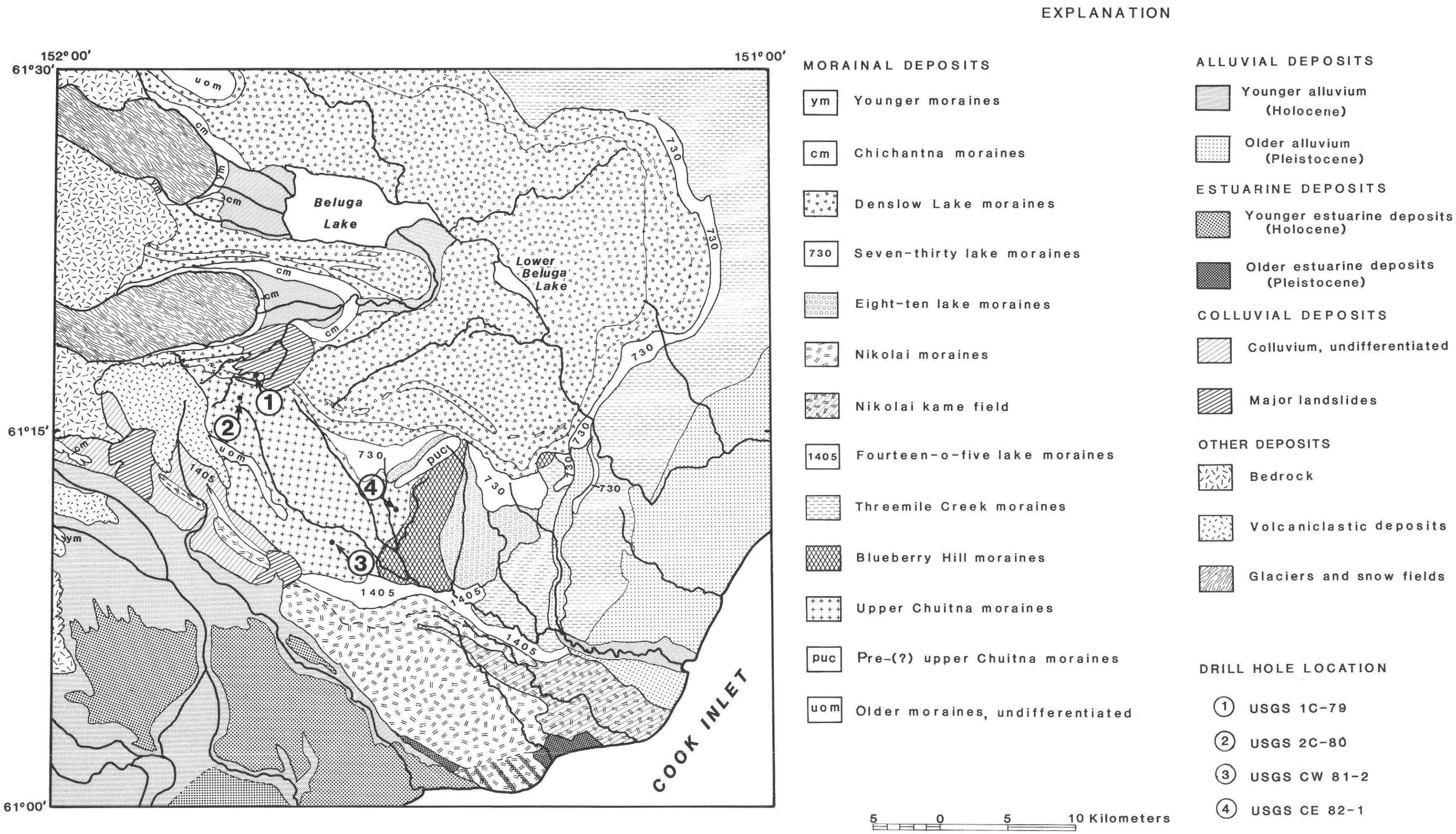

Figure 2. Generalized surficial geologic map of the Beluga plateau and vicinity, upper Cook Inlet region, Alaska.

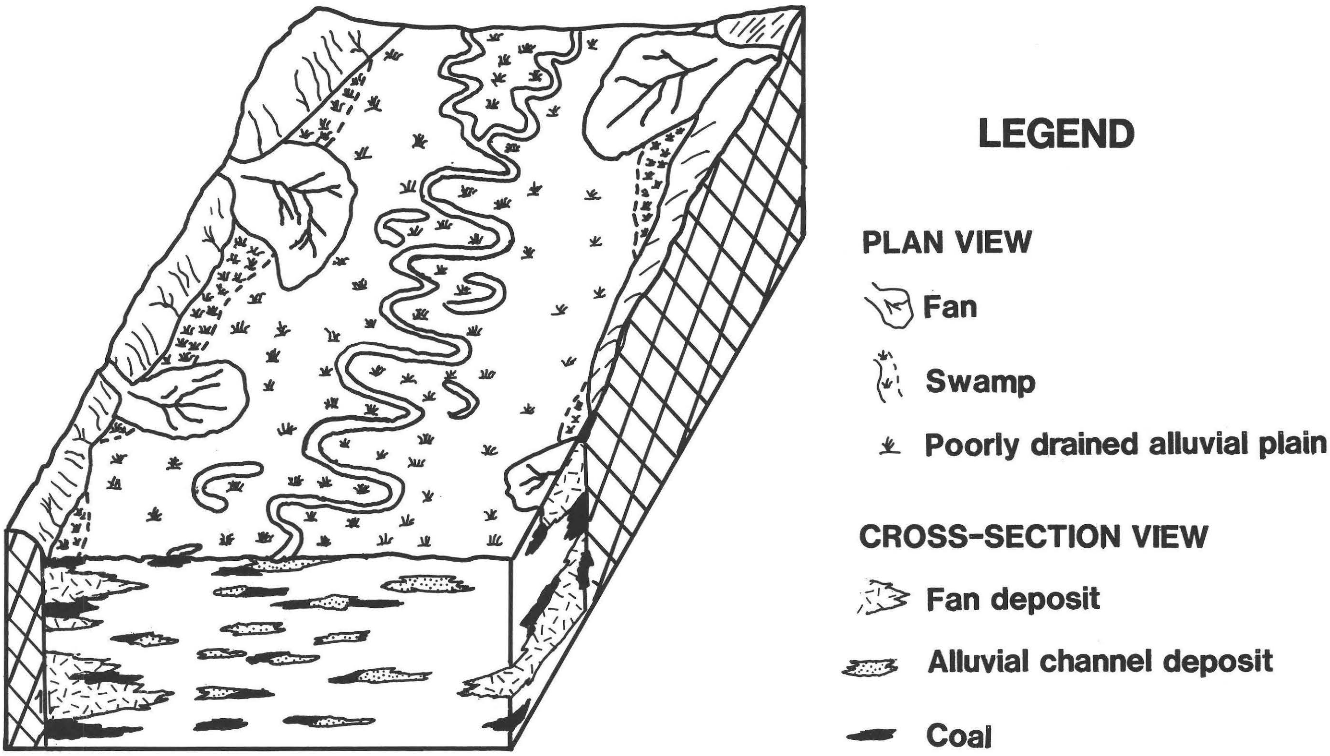

Figure 3. Depositional environment model of the Tyonek Formation showing a poorly drained alluvial basin (Hite, 1976).

Susitna River mouth and lower Susitna Flats area of the upper Cook Inlet region, shows a modern example of such an environment with modern and older Susitna alluvium and intertidal areas.

Lithologic Distribution

Detailed lithologic logs of each drill hole, along with physical properties and geotechnical data, were presented by Odum (1986). Thin accumulations of organic material and volcanic ashbeds that total less than one meter in thickness are directly beneath the ground surface. Underlying these surficial deposits are diamictons (presumably of glacial origin and of Quaternary age), which in turn, overlie the Tyonek Formation.

Figures 5*A*–*D* are generalized stratigraphic columns of USGS drill holes: Capps coal field, (*A*) 1C–79 and (*B*) 2C–80; and Chuitna coal field, (*C*) CW 81–2 and (*D*) CE 82–1. Histograms that accompany the generalized lithologic logs of figures 5*A*–*D* indicate the abundance, expressed as a percentage of the total cored-hole depth, of each major lithology within the drill hole. Table 1 lists the lithologic unit characteristics (thinnest, thickest, average thickness, and relative abundance for major lithologies) for the four drill holes.

Figure 6 summarizes information on the abundance of each major lithology that was cored in the the two coal fields. Arrows on the right side of the figure indicate whether the abundance of a lithology is greater in the Capps field (arrow pointing downward) or in the Chuitna field (arrow pointing upward). Table 1 also indicates that the maximum thicknesses of the finer grained lithologies are greater in the Chuitna area than in the Capps area. These differences in lithologic abundance between the two areas probably reflect the more basinward location of the Chuitna area with respect to the basin-margin location of the Capps area. It may also reflect a basin-wide change in depositional energy, such as a slowing of margin uplift and (or) basin subsidence during early and middle Miocene time (Kirschner and Lyon, 1973).

GEOTECHNICAL RESULTS AND INTERPRETATION

Durability

Durability, with respect to geologic materials, is defined as the resistance of material to weathering and disintegration over time. The slake-durability-index test provides a means of estimating the deterioration potential of a geologic material to climatic wetting and drying (Franklin and Chandra, 1972). These index tests are used

Figure 4. Photograph of Susitna River mouth and lower Susitna Flats area of the upper Cook Inlet region, showing a modern example of a poorly drained alluvial-basin environment.

here to compare lithologies in different localities as well as to determine engineering weatherability.

Slake-Durability-Index Test

In this paper, slake-durability-index test results are reported in percent of the total sample weight that remains after two cycles of testing. A test cycle consists of: (1) Drying and weighing ten roughly spherical specimens with initial individual sample weights between 40 and 60 g, (2) tumbling the specimens in a mesh cage with 2-mm openings while partially submerged in a water tank for ten minutes, and (3) drying and reweighing the specimen material that remains in the cage. The index is calculated by dividing the weight of the remaining material by the original sample weight times 100 (ISRM, 1972b). A high slake-durability-index percentage indicates that the material has a relatively high resistance to disintegration due to climatic wetting and drying.

Slake-durability-index tests were performed

Table 1. Strata characteristics by lithology for each drill hole
[--- indicates information not available; n.a. indicates not applicable]

Lithology	Thickest unit (m)	Thinnest unit (m)	Average thickness (m)	Sandstone core loss (percent)	Total core (percent)
CAPPS COAL FIELD: USGS 1C-79					
Diamicton......	9.5	---	---	n.a.	7.9
Sandstone......	55.2	0.1	---	72.4	55.1
Siltstone......	1.6	0.1	0.5	n.a.	6.7
Claystone......	8.5	0.2	1.0	n.a.	10.5
Carbonaceous... claystone.	1.4	0.1	0.5	n.a.	4.6
Coal...........	7.6	0.2	2.3	n.a.	15.2
CAPPS COAL FIELD: USGS 2C-80					
Diamicton......	1.8	---	---	n.a.	3.0
Sandstone......	11.8	0.4	---	76.0	28.8
Siltstone......	14.0	0.2	4.3	n.a.	34.2
Claystone......	0.8	0.2	0.4	n.a.	2.3
Carbonaceous... claystone.	2.3	0.1	0.6	n.a.	9.4
Coal...........	4.3	0.1	0.9	n.a.	22.3
CHUITNA COAL FIELD: USGS CW 81-2					
Diamicton......	1.8	---	---	n.a.	3.7
Sandstone......	11.8	0.4	5.4	70.6	20.3
Siltstone......	14.0	0.2	4.6	n.a.	20.0
Claystone......	0.8	0.2	2.5	n.a.	9.8
Carbonaceous... claystone.	2.3	0.1	1.3	n.a.	17.6
Coal...........	4.3	0.1	3.3	n.a.	28.8
CHUITNA COAL FIELD: USGS CE 82-1					
Diamicton......	3.1	---	---	n.a.	2.7
Sandstone......	16.1	0.5	5.8	62.5	28.3
Siltstone......	10.7	0.1	2.0	n.a.	32.5
Claystone......	1.6	0.1	1.0	n.a.	8.8
Carbonaceous... claystone.	2.5	0.2	0.9	n.a.	10.2
Coal...........	10.8	0.1	2.7	n.a.	17.5

primarily on clay-bearing lithologies (siltstone, claystone, and carbonaceous claystone). In addition, tests were run on seven intact pieces of very fine grained, weakly lithified sandstone and a few pieces of subbituminous coal. Figure 7 compares the distribution of durability-test results by specific lithologies, for samples collected from the two coal fields. Presented in table 2, in order of increasing durability of the lithologies, are the range and mean values that were calculated from a composite of all tests shown in figure 7, regardless of their coal field association.

Sandstone Units

In each drill hole, an individual sandstone unit was found to be the thickest continuous lithologic unit. A

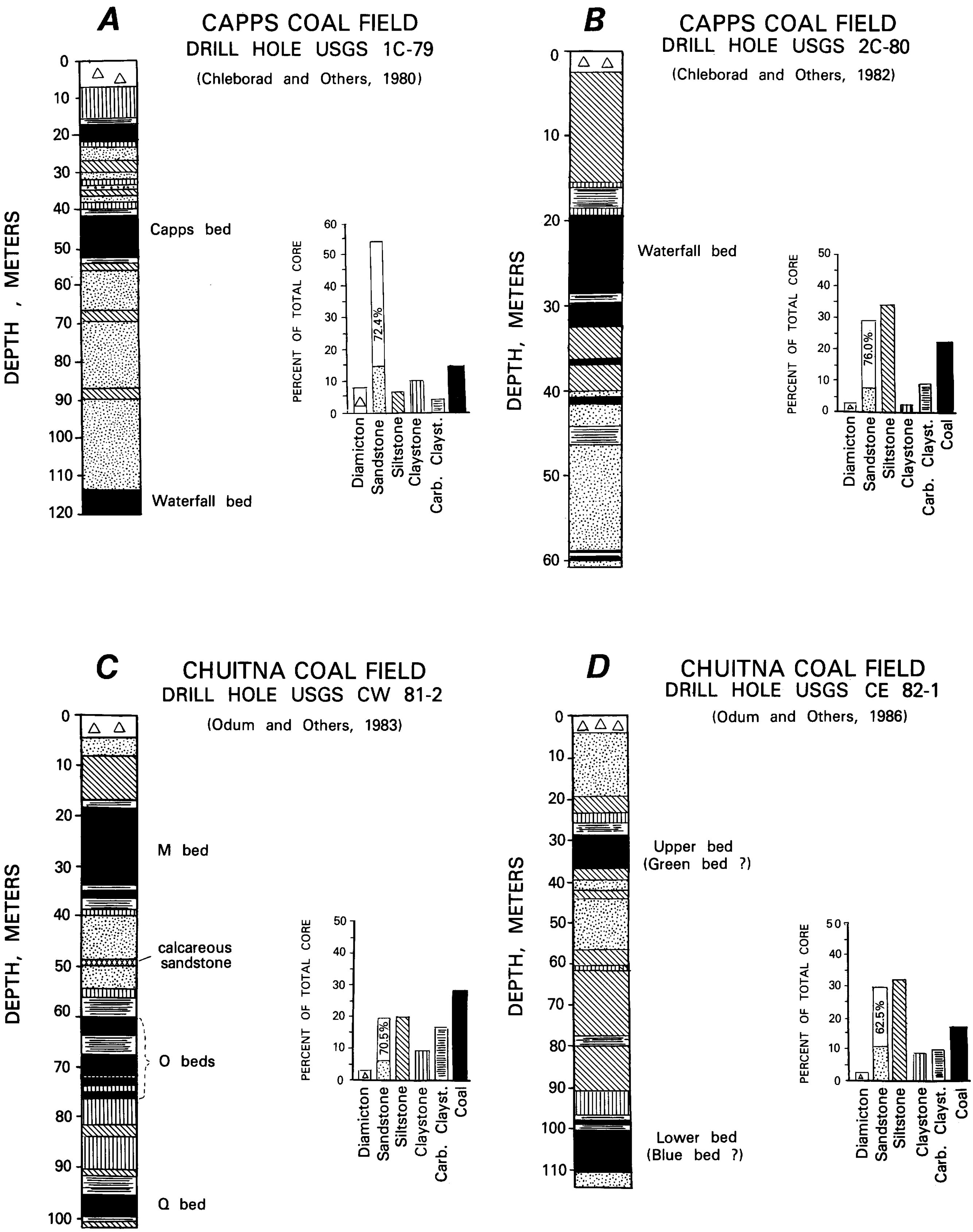

Figure 5. Generalized stratigraphic columns for U.S. Geological Survey drill holes. Histograms accompanying figures indicate the percentage of a specific lithology present within that drill hole with respect to the total cored thickness. The number in the sandstone column indicates the percentage of encountered sandstone that was not recoverable.

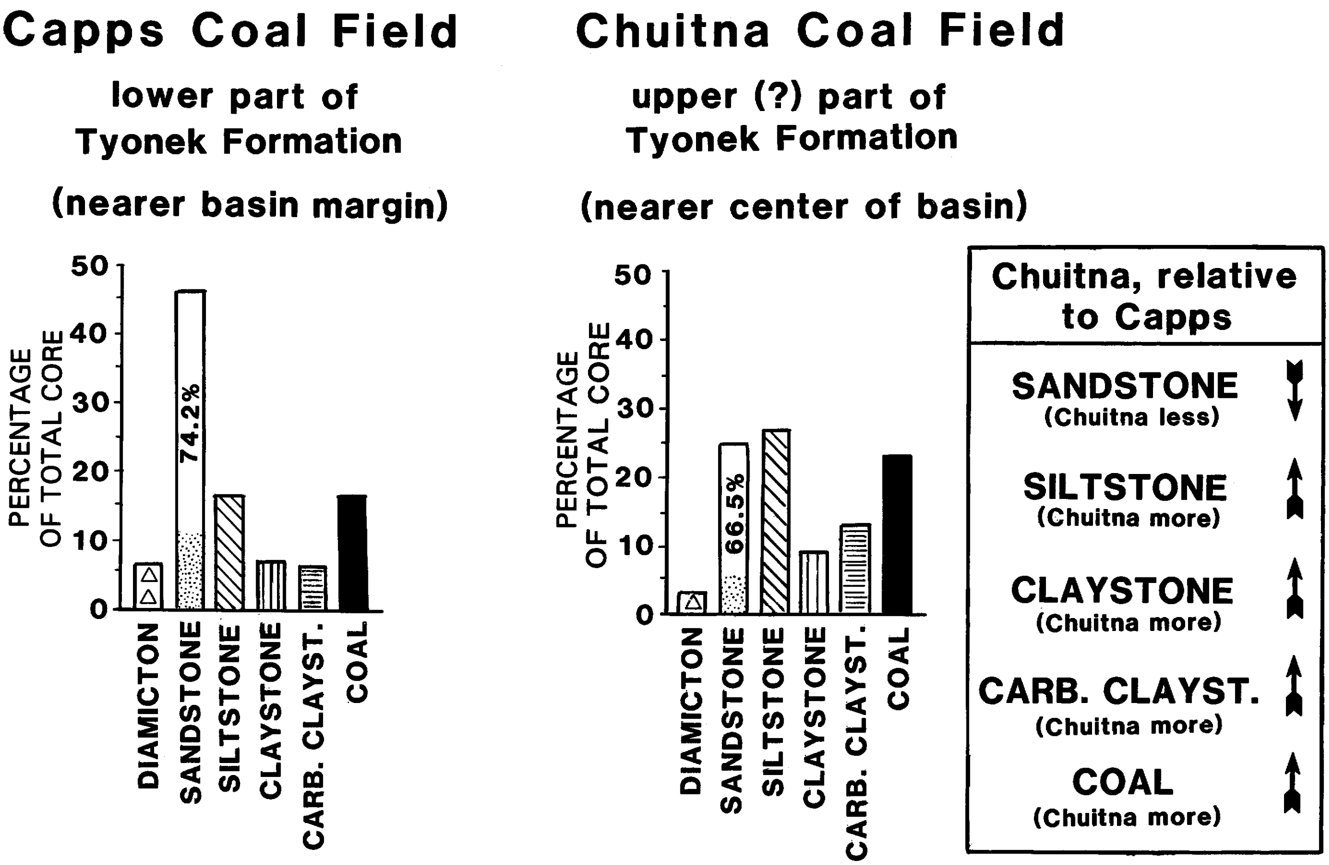

Figure 6. Histograms showing the overall trend from a coarser grained to a finer grained lithologic character between the Capps coal field (basin-margin locality) and the Chuitna coal field (more basinward locality). Arrows indicate an increase (upward pointing arrow) or decrease (downward pointing arrow) in rock type between the two areas. The number in the sandstone column indicates the percentage of encountered sandstone that was not recoverable.

single sandstone unit in drill hole USGS 1C–79 measured approximately 55 m in thickness, and in the other three drill holes the maximum thickness of a single sandstone unit ranged from 12 to 16 m (table 1). The majority of the sandstone units encountered in all four drill holes, however, were generally so weakly lithified that they were nonrecoverable (table 1, sandstone percent loss column). These nonrecoverable sandstone units must be considered to have no durability for engineering purposes and could best be described as loose, very fine to coarse grained sands with an occassional gravel lens, rather than sandstone.

The slake-durability-index mean, for recoverable sandstone core, of 19.8 percent (table 2), is derived from seven test samples that were collected from all four drill holes. These samples were typically very fine to fine grained and contained appreciable amounts of silt- and clay-sized particles. Some samples contained thin but recognizable lamina of siltstone, claystone, and carbonaceous materials. The presence of carbonate cementing material, detectable by diluted (15 percent) hydrochloric acid, in the sandstones and other lithologies was for all practical purposes nonexistent in the Capps coal field core and occurred rarely in the Chuitna coal field core. X-ray powder diffraction analysis identified the carbonate cementing material as calcite (M.E. Brownfield, oral commun., 1986). The most notable occurrence of cementing appeared in drill hole USGS CW 81–2, where a 1.1–m-thick unit of coarse sand and gravel was cored within a thick section of otherwise nonrecoverable, loose, fine- to medium-grained sand. In addition, near the bottom of drill hole USGS CE 82–1, a thin 0.3–m-thick carbonate-cemented unit was also encountered. A few other occurrences of cementing were found in some siltstone units that were cored from the Chuitna coal field.

Strength

Point-Load-Strength Test

The point-load-strength test is an inexpensive and rapid field-orientated means of approximating unconfined compressive strength from measured tensile

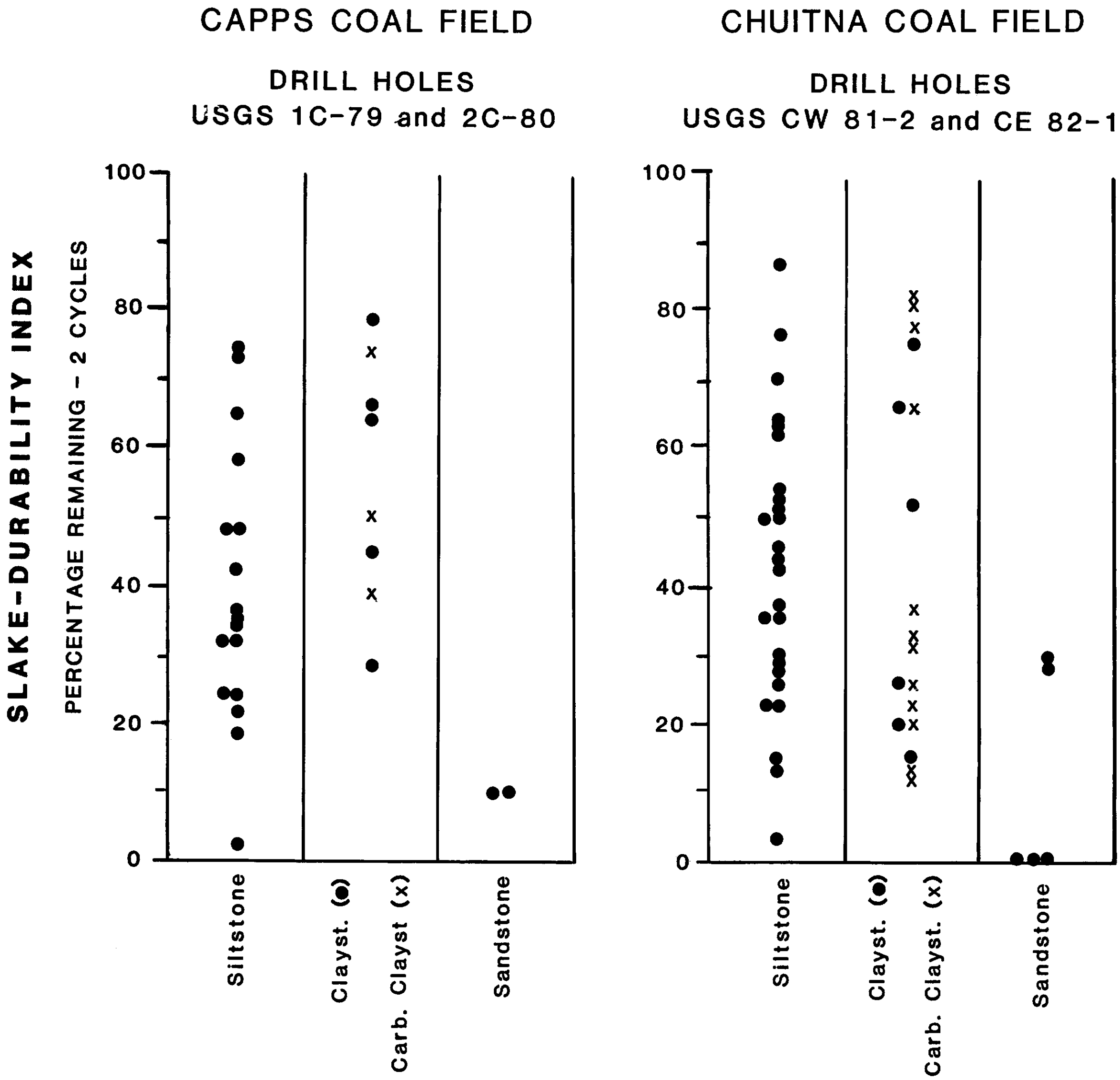

Figure 7. Graph comparing the distribution of slake-durability-index values, by lithology, of the Capps and Chuitna coal fields.

Table 2. Ranges and means of slake-durability-index values
[Results grouped by lithology, without respect to drill hole origin, and arranged in order of increasing durability]

Lithology	Number of test specimens	Range (percent)	Mean (percent)
Sandstone.......	7	0-30	19.8
Siltstone.......	40	14-86	40.3
Carbonaceous.... claystone.	13	12-82	46.3
Claystone.......	13	15-75	49.1

strength. The point-load strength (I_s) is defined as P/D^2, where D is the diameter between the loading points of the testing apparatus and P is the load applied. As prescribed by the International Society of Rock Mechanics (ISRM, 1972a), the point-load strength value is "normalized" to a reference diameter of 50 mm using the chart developed by Brock and Franklin (1972). The resultant value, $I_s(50)$, is then referred to as the point-load strength index. Bieniawski (1975) has recommended that the reference diameter be changed to 54 mm, which is the standard core size for the Rock Quality Determination (RQD) system (Deere, 1968) and also the standard core size for unconfined-compressive strength tests (American Society for Testing of Materials (ASTM) 1971; ISRM, 1972b; Abeyesekera and Lovell, 1981). Hassani and others (1980) presented a different "normalization" chart and accompaning diameter-correction equations, as an alternative to the Brock and Franklin (1972) chart currently being used by ISRM.

In this study, the point-load strength values for the diametral test (load applied approximately parallel to the bedding planes and normal to the core axis) were "normalized" to the ISRM prescribed diameter of 50 mm, using Brock and Franklin's (1972) chart. In the literature (Dunrud and Osterwald, 1980), there is more than one empirically determined coefficient (ranging from 22 to 35) by which the point-load strength index is multiplied to obtain an approximation of unconfined compressive strength. For consistency with previously published field-test data, all the approximate unconfined-compressive strength values are computed by multiplying the resultant value ($I_s(50)$) by Brock and Franklin's empirical coefficient of 24.

The point-load-strength-test method is optimally applied to core having horizontal to low-angle bedding so that diametral tests are parallel to the bedding planes, and axial tests are perpendicular to bedding planes. Both drill holes (IC–79 and 2C–80) in the Capps coal field encountered strata that show essentially horizontal bedding. Drill holes USGS CW 81–2 and CE 82–1 in the Chuitna coal field encountered zones of strata with dips of 5–20° and 25–35°, respectively. However, diametral tests on the Chuitna cores still failed along recognizable bedding planes. For a few axial tests, however, the degree of dip made it difficult to obtain through-breaks; part of the failure occurred along bedding planes. Test results that were known to be related to improper failure were not used in the subsequent numerical analysis.

Figure 8 displays the approximate unconfined-compressive strength values in terms of loading orientation for each drill hole. Also displayed is the ratio of strength-perpendicular-to-bedding to strength-parallel-to-bedding; this ratio is termed strength anisotropy. The results are grouped by lithology and graphed in descending stratigraphic order. These figures indicate little evidence for an increase in approximate unconfined compressive strength with increasing depth for any individual lithology over the relatively shallow depths that were penetrated. Figure 9 compares and summarizes the range and mean values of both axial and diametral tests performed on the Capps and Chuitna coal field cores. The horizontal bars in each column indicate the mean value of tests for that lithology.

Figure 9 shows that ranges and means of strength test results for the finer grained lithologies (siltstone, claystone, and carbonaceous claystone) for the Capps coal field cores are very similar regardless of loading orientation. The testable sandstone samples, however, are typically very fine to fine grained and (or) silty to clayey, and they show a small range of strengths and a very low mean strength. Both sandstone and siltstone from the Chuitna coal field cores show ranges and means similar to the corresponding lithologies in the Capps field. Chuitna field claystone and carbonaceous claystone, however, show wider ranges for diametral tests and narrower ranges for axial tests when compared to similar lithologies in the Capps field. The lower mean for axial tests on the Chuitna claystone, as well as the differences in the ranges, may be a reflection of the 5–20° bedding-plane dips that occur in some samples. Overall, however, the claystone mean values are not appreciably different from those determined for the Capps field cores. The subbituminous coals have strength values notably higher than those of the other common lithologies and overall mean values are approximately the same between the two fields.

Not shown on figure 9 are two diametral tests that were performed on carbonate-cemented lenses, or nodules, that are located within weakly lithified sandstone units from drill hole USGS CW 81–2 (fig. 5*C*). A weakly cemented sample from a depth of 39.9 m measured 6.4 MN/m^2, while a sample from the extremely well cemented, 1.1-m-thick, pebbly to coarse-grained sandstone unit at 50.1 m had a very high measured strength of 55.2 MN/m^2.

Table 3 lists the range, mean, and anisotropy values for all tests, by lithology and orientation, without respect to coal field. There appears to be a rough correlation between increasing strength and decreasing grain size similar to that observed in the ordering of the slake-durability-index results. Anisotropy values reflect the increasing fissile character of the rocks due to the overall increase in clay-mineral and carbonaceous content with decreasing grain size. The uncemented sandstone units have little to no strength.

Laboratory Unconfined Compressive Strength

Selected core samples from the four drill holes were prepared and tested according to ASTM (1971) methods (D 2938–71a). Specimens had a length-to-diameter ratio

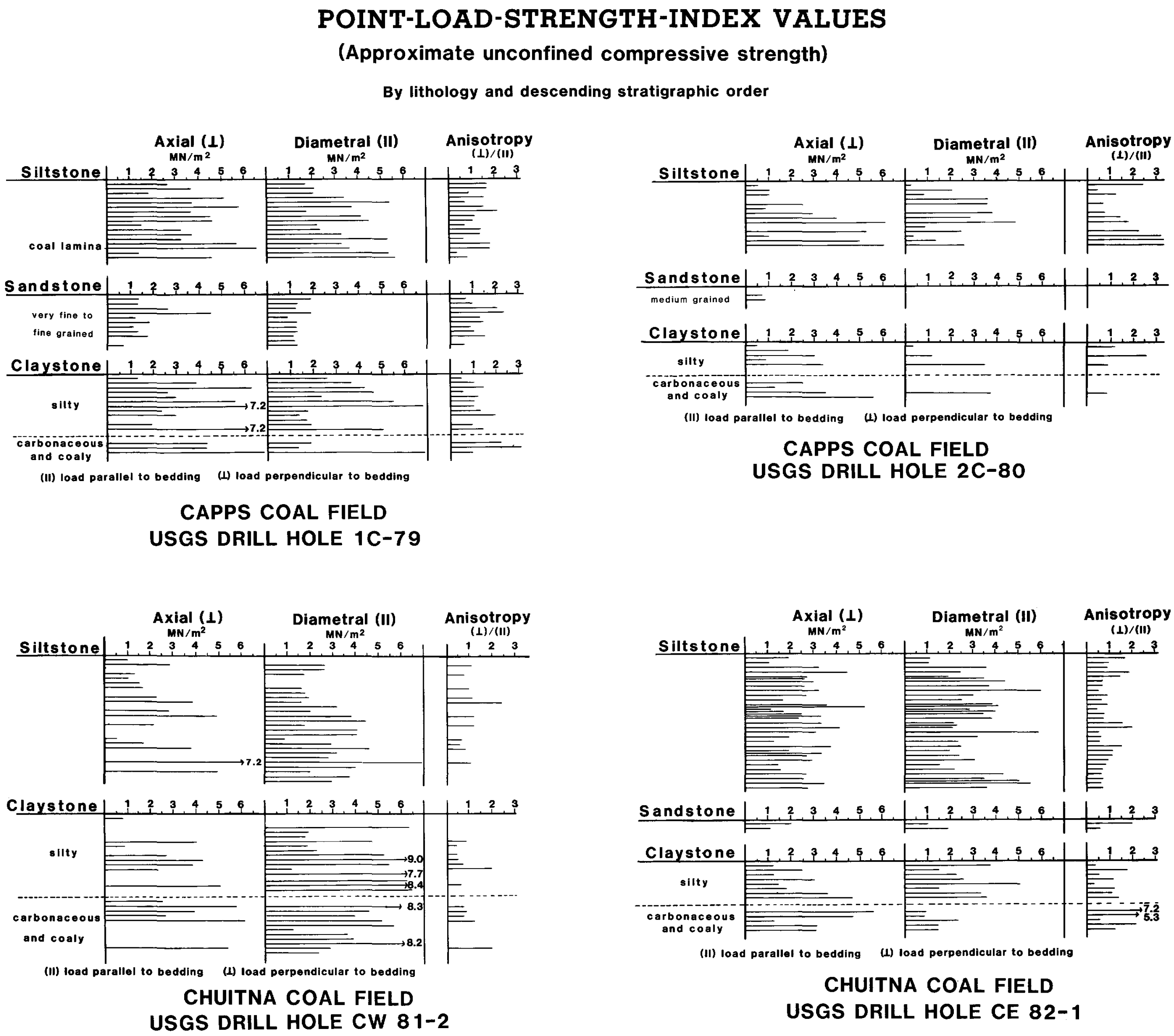

Figure 8. Point-load-strength-index values of specific lithologies are arranged by descending stratigraphic order. Values have been "normalized" to a reference diameter of 50 mm and multiplied by Brock and Franklin's (1972) empirical coefficient of 24 to obtain approximate unconfined-compressive strength values.

of 2.0–2.5, and core-cylinder end surfaces were within 0.024 mm (0.001 in.) of perpendicularity with the core axis. The moisture content of the samples was maintained as close to natural conditions as possible by rapid waxing in the field and subsequent storage in a controlled high-humidity room at the receiving laboratory. Due to the naturally weak nature of many of the lithologies of the Tyonek Formation that was previously demonstrated by the results of slake-durability and point-load-strength-index testing and by the additional sample loss incurred during specimen preparation (paralleling of cylinder ends), test results must be considered somewhat biased toward the more competent samples of a specific lithology.

Figure 10 shows the distribution of test results with respect to specific lithologies and allows a comparison of similar lithologies between the two coal fields. Table 4 presents the range and mean values for a composite of all tests. The ordering of lithologies with respect to mean increasing strength is similar to that determined from tests of the axial point-load strength index in that siltstone is slightly stronger than claystone.

The wide range of strength values that were measured for the four samples from the 1-m-thick carbonate-cemented, pebbly to coarse-grained sandstone unit (fig. 10) from drill hole USGS CW 81-2 (fig. 5C), probably reflects varying degrees of cementation and grain

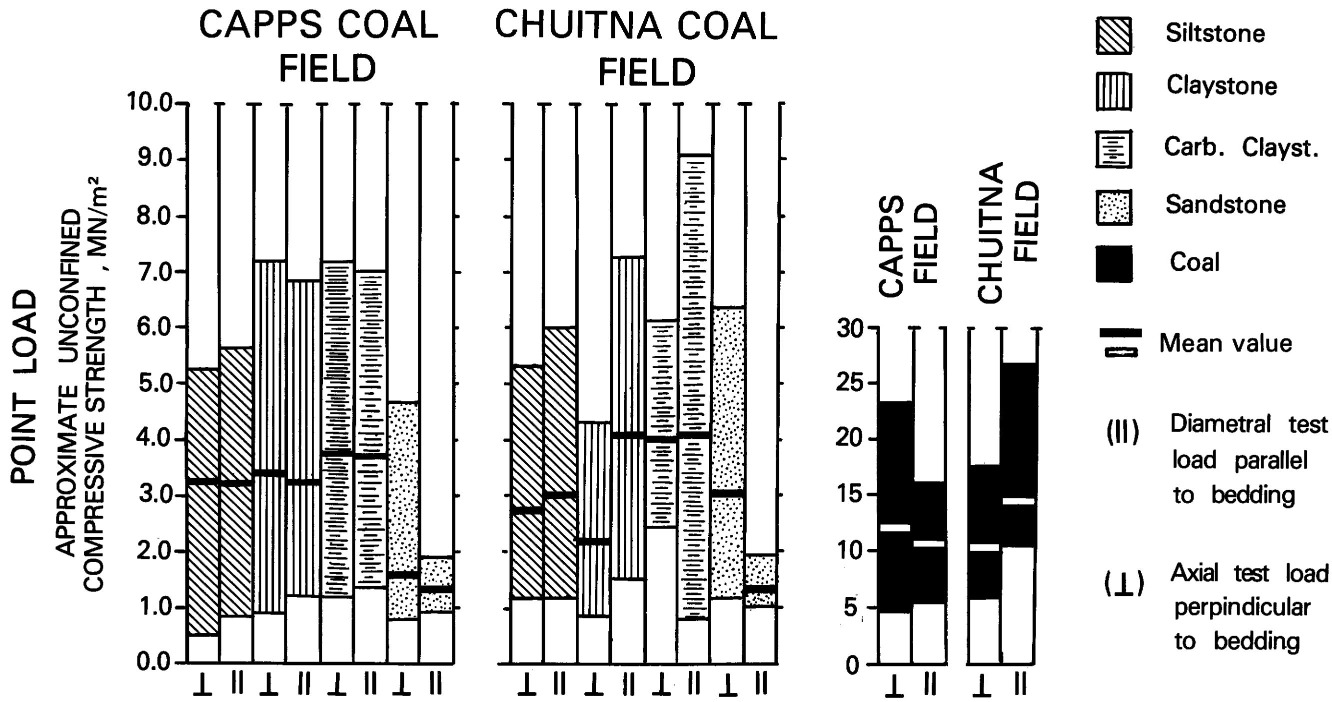

Figure 9. Comparison of the range and mean values of point-load-strength indexes by lithology. Values are graphed in terms of approximate unconfined compressive strength and loading orientation.

Table 3. Ranges and means of approximate unconfined-compressive strength derived from axial and diametral point-load tests without respect to coal field

[Results are grouped by lithology and loading orientation and arranged in order of increasing anisotropy. (A), axial loading (perpendicular to bedding); (D), diametral loading (parallel to bedding); --- indicates value cannot be calculated]

Lithology	Number of samples tested	Range (MN/m^2)	Mean (MN/m^2)	Anisotropy (A/D)
Sandstone.......	(A) 13	0.6-2.6	1.5	---
	(D) 15	0.9-1.9	1.4	1.07
Siltstone.......	(A) 77	0.5-7.2	3.2	---
	(D) 86	0.9-6.9	3.1	1.13
Claystone.......	(A) 29	0.4-7.2	2.8	---
	(D) 33	0.8-7.0	3.7	1.30
Carbonaceous....	(A) 16	1.2-7.2	3.7	---
claystone.	(D) 22	0.8-9.2	4.0	1.56
Coal............	(A) 24	4.6-23.4	11.9	---
	(D) 19	5.5-26.4	11.9	1.83
Calcareous...... sandstone.	(D) 2	6.2-55.2	30.8	---

size. These specimens had the visual appearance of and tested very much like concrete.

Figure 11 is a chart relating "Qualitative Hardness Terminology" to laboratory-determined unconfined-compressive-strength values (Jennings and Robertson, 1968). The horizontal bars, to which specific hardness terms have been applied, represent the range of unconfined-compressive strengths that were compiled from literature by Jennings and Robertson (1968). The pattern-shaded areas represent the range of terms that could be applied to the laboratory test results on rocks from the Tyonek Formation. Except for the subbituminous

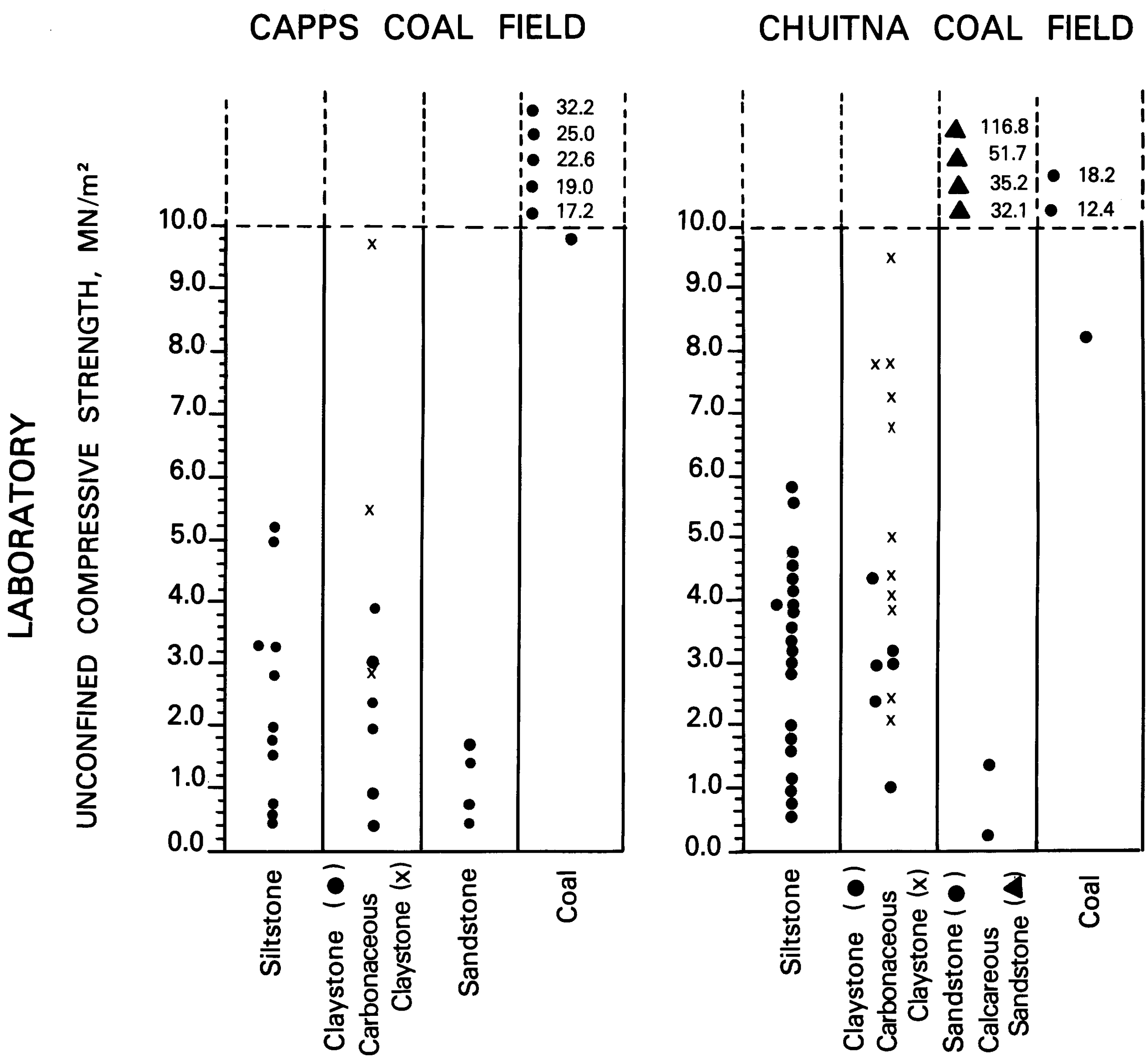

Figure 10. Lithologic comparison of laboratory-derived unconfined-compressive-strength values.

coal and the small samples of carbonate-cemented pebbly sandstone, the cored lithologies of the Tyonek Formation are characterized as having hardnesses that range from very soft soil to soft rock.

Grain, Natural Bulk, and Dry Bulk Density

All values fall within the normal range of values associated with similar sedimentary lithologies. Average natural-bulk-density values, along with average ultrasonic compressional- and shear-wave velocities, were used to calculate the representative dynamic Poisson's ratio and elastic moduli for the Chuitna coal field cores.

Grain-Size Distribution, Atterberg Limits, and Activity Index

Core samples were disaggregated and tested for grain-size distribution and Atterberg limits. This information was used to refine descriptions of fine-grained lithologies (Odum, 1986). Atterberg limits reflect the quantity of water that is attracted to the particle surfaces. As grain size decreases, surface area increases and water content will be increasingly influenced by the amount of clay in a material. The activity index, defined by Skempton (1953) as the ratio of the plasticity index to percent-by-weight of particles finer than 0.002 mm, is an indication of clay mineralogy and swelling potential. The range and mean clay-activity index values for the various clay-bearing lithologies in the Tyonek Formation are listed below.

Clay Activity Index

Lithology	Range	Mean
Claystone	0.47–1.00	0.60
Carbonaceous claystone.	0.27–1.33	0.63
Siltstone	0.30–1.35	0.85

Based on Skempton's (1953) classification, these lithologies have "low to normal" activity, are likely to contain kaolinite- and illite-group clay minerals, and have "medium" swelling potential.

Clay Mineralogy

Clay mineralogy was determined by X-ray analysis according to procedures presented by Schultz (1964). Analytical results are listed in table 5 in terms of clay-mineral group (kaolinite, illite, mixed layer, montmorillonite, and chlorite) abundance. Kaolinite and illite groups are generally the most abundant and, in many instances, make up 40–60 percent of the samples' clay fraction. Only three samples, all from drill hole USGS CW 81-2, show montmorillonite abundance greater than 10 percent; no sample exceeded 20 percent. Abundances of the mixed-layer clay group were very similar to the abundances calculated for the montmorillonite group.

Of mineralogical note is the presence of the strontium-rich hydrated-aluminophosphate mineral goyazite (P.D. Blackman, written commun., 1981). This mineral is present in a 3-cm-thick volcanic tuff(?) at a depth of 52.4 m, which is 2.1 m above the base of the Capps coal bed in drill hole USGS 1C-79.

Geochemical Analysis

Whole-rock chemical composition and trace-element analysis of the non-coal lithologies from the Capps coal field was reported by Hinkley and others (1982). Similar analysis for the Chuitna coal field cores is currently being prepared by J.R. McNeal and others, U.S. Geological Survey. Chemical and trace-element analysis of Quaternary soils in the vicinity of the Capps drill sites has been reported by Gough and Severson (1983) and Severson and Gough (1983).

Affolter and Stricker (1985) performed proximate and ultimate analyses and heat-of-combustion and forms-of-sulfur measurements and determined the abundance of 40 major, minor, and trace elements. These data, along with an evaluation of low-temperature-ash mineralogy, were compiled from the analysis of 43 samples that were taken from eight coal beds: the Capps and Waterfall (from the Capps field), and the M, O, Q, and three unnamed beds (from the Chuitna field). Affolter and Stricker (1985) summarized as follows:

> "Analyses show an apparant rank that ranges from subbituminous B to subbituminous C, with a variable ash content of 4.7–46.5 percent and one of the lowest sulfur ranges reported for any United States coal of 0.08–0.33 percent. Nearly half the elements analyzed (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 >0.8). Mineral composition of the low-temperature ash is predominantly kaolinite and mica-type clays with varying amounts of quartz. These data suggest that many of the

Table 4. Ranges and means of laboratory unconfined-compressive-strength test data based on a composite of all samples from the Capps and Chuitna coal fields
[Arranged in order of increasing strength]

Lithology	Number of samples tested	Range (MN/m^2)	Mean (MN/m^2)
Sandstone	6	0.2–1.7	1.0
Claystone	12	0.6–4.4	2.6
Siltstone	33	0.5–5.1	3.0
Carbonaceous claystone.	15	2.2–9.7	5.8
Coal	9	8.6–32.2	18.4
Calcareous sandstone.	4	32.1–116.8	59.0

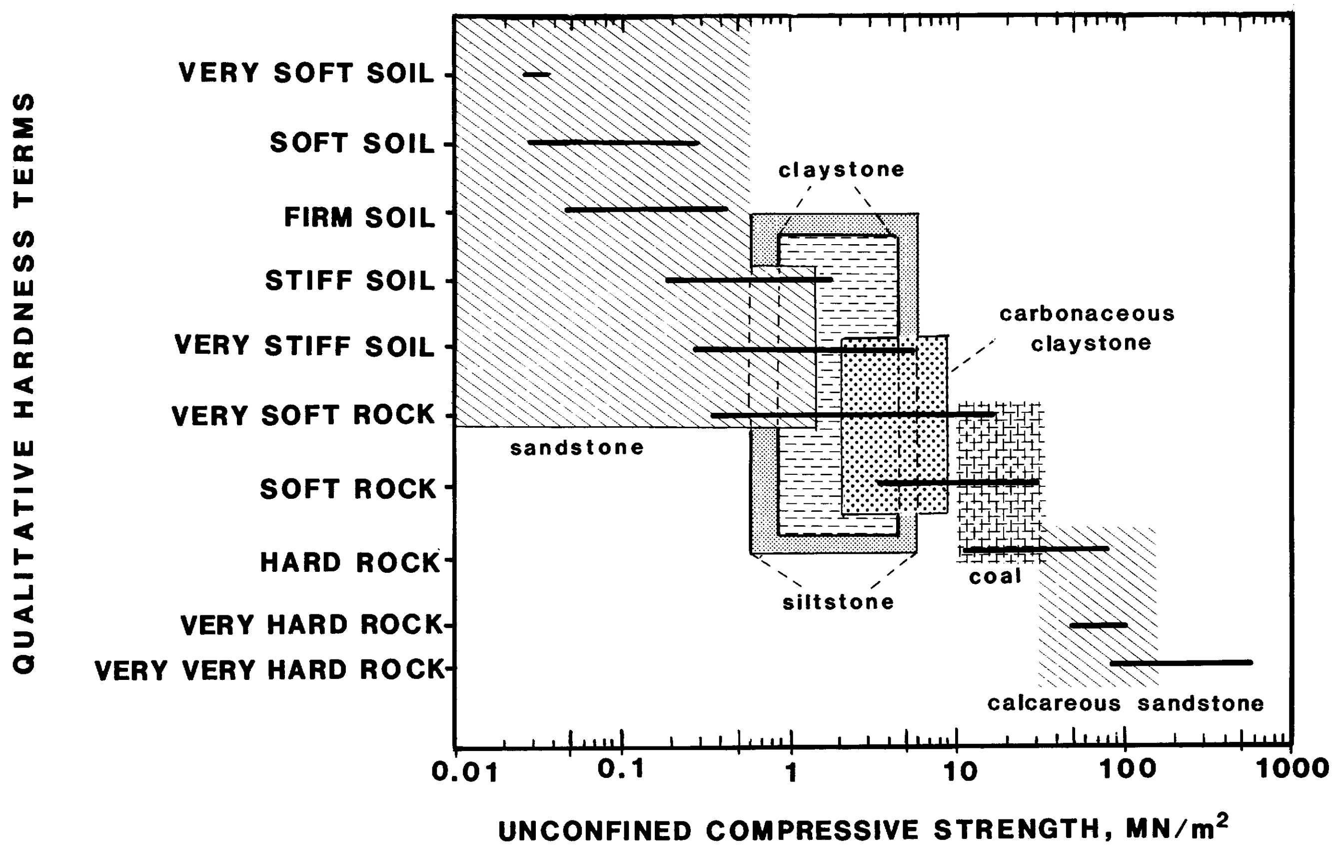

Figure 11. Range of "qualitative hardness terms" associated with the lithologies of the Tyonek Formation, based on the range of laboratory-derived unconfined compressive strengths. Horizontal bar indicates range of strengths determined by various workers.

elements that vary with ash content may also be associated with the clay minerals. The M bed, in the Chuitna field, has the lowest ash content and the lowest concentration of ash-correlated elements, whereas the Capps bed has the highest ash content, and therefore, the highest concentration of these elements. The variability of content is probably a direct result of the proximity of the original peat swamp to nearby tectonically active highlands. The peat is thought to have accumulated in non-marine swamps as indicated by the low-average forms of sulfur for all eight coal beds (0.13 percent organic sulfur, 0.02 percent sulfate sulfur, and only 0.01 percent pyritic sulfur). Trace elements that normally show positive correlation with sulfur in lower United States coals, such as As, Cd, Co, Fe, Mo, Ni, Pb, and Zn, are low in concentration for tested coal from the Tyonek Formation."

Ultrasonic Compressional- and Shear-Wave Velocity

Ultrasonic testing uses high-frequency (generally in excess of 20 kilocycles per second) mechanical vibrations to characterize the physical properties of an elastic material, for example, soil and rock. The equipment system used in this study was constructed by David R. Cunningham (U.S. Geological Survey) according to specifications outlined by Dr. Richard W. Stephenson, University of Missouri-Rolla. The system consists of: (1) A pulse generator capable of delivering a variable-voltage direct-current pulse with pulse widths of 1–100 microseconds and pulse intervals of 1-99 milliseconds, 2) an oscilloscope, 3) a sample support device, and 4) two ultrasonic probes (one transmitter and one receiver). The coupling medium used for bonding of the ultrasonic probes to the rock specimen was silicon grease for compressional-wave transmission and phenalsilicitate for shear-wave transmission. Test specimens, in general, had a length-to-diameter ratio of at least 2:1.

Intact, weakly lithified, and noncarbonate-cemented-sandstone specimens suitable for testing could be obtained only from drill hole USGS CE 82-1. All carbonate-cemented sandstone specimens came from small units scattered throughout the 15-m-thick, loose to weakly lithified sandstone unit that was penetrated by drill hole USGS CW 81-2. The four coal specimens that were selected for testing from drill hole USGS CE 82-1 broke along high-angle fractures during the sample preparation.

Table 5. Relative abundance of clay-mineral groups for all four drill holes
[Abundance ranges: 1 = 40-60 percent, 2 = 20-40 percent, 3 = 10-20 percent, 4 = less than 10 percent]

Depth of sample (m)	Clay-mineral groups					Lithology
	Chlorite	Kaolinite	Illite	Montmorillonite	Mixed layer	
USGS IC-79						
11.9	3	2	1	4	4	Claystone.
15.4	3	2	2	4	3	Carbonaceous claystone.
17.6	3	2	2	4	4	Silty claystone.
18.6	4	1	2	4	4	Clayey siltstone.
23.5	3	2	2	4	3	Sandy siltstone.
28.9	3	2	2	4	3	Siltstone.
32.6	3	2	2	4	4	Carbonaceous claystone.
39.2	3	2	2	4	4	Claystone.
42.4	3	2	2	4	3	Carbonaceous claystone.
45.6	2	2	2	4	4	do.
46.1	2	1	2	4	4	Siltstone.
115.3	2	1	3	4	4	Carbonaceous claystone.
115.5	3	1	3	4	4	do.
15.8	2	1	3	4	4	do.
USGS 2C-80						
1.9	2	1	3	4	4	Sandy siltstone.
3.4	2	2	2	4	4	Clayey siltstone.
4.7	2	1	2	4	4	do.
5.2	3	1	3	4	4	do.
7.2	2	1	3	4	4	do.
9.2	2	1	2	4	4	do.
11.9	2	2	2	4	4	do.
16.2	2	1	2	4	4	Claystone.
17.7	2	1	2	4	4	Carbonaceous claystone.
23.6	2	1	2	4	4	do.
29.6	2	1	2	4	4	do.
33.3	2	1	3	4	4	Carbonaceous siltstone.
35.7	2	1	3	4	4	do.
40.2	2	1	3	4	4	Siltstone.
44.8	2	1	3	4	3	Carbonaceous claystone.

Table 5. Relative abundance of clay-mineral groups for all four drill holes—Continued
[Abundance ranges: 1 = 40-60 percent, 2 = 20-40 percent, 3 = 10-20 percent, 4 = less than 10 percent]

Depth of sample (m)	Clay-mineral groups					Lithology
	Chlorite	Kaolinite	Illite	Montmorillonite	Mixed layer	
USGS CW 81-2						
11.2	3	2	2	3	4	Carbonaceous siltstone.
16.6	4	1	1	4	4	Clayey siltstone.
35.1	4	4	1	4	4	Carbonaceous claystone.
40.7	4	1	2	4	3	Sandstone.
57.2	3	1	2	4	4	Carbonaceous claystone.
64.7	4	1	2	4	4	Carbonaceous claystone.
67.7	3	2	1	4	4	do.
73.9	2	3	3	4	4	Claystone.
74.3	4	1	1	4	4	do.
77.4	4	1	3	4	4	Clayey siltstone.
81.6	3	1	2	4	4	Carbonaceous claystone.
84.7	2	1	2	3	4	Clayey siltstone.
88.6	3	1	4	3	2	do.
90.1	4	1	2	3	4	Claystone.
101.6	3	1	2	4	3	Carbonaceous siltstone.
USGS CE 82-1						
23.6	4	1	2	4	4	Siltstone.
24.8	3	2	1	4	4	Claystone.
37.6	3	2	1	4	4	Siltstone.
44.7	4	4	1	4	4	do.
57.2	3	1	2	4	4	Carbonaceous claystone.
67.7	4	2	1	4	4	Clayey siltstone.
78.7	3	1	2	4	4	Carbonaceous claystone.
95.2	3	1	2	4	4	Claystone.
98.0	3	2	2	4	2	Carbonaceous claystone.
99.3	3	2	1	4	4	do.

Figure 12 displays the distribution of compressional- and shear-wave velocities for specific lithology samples from the two Chuitna coal field holes, and table 6 presents the velocity range and mean values for the same samples. In general, compressional- and shear-wave velocity range and mean values for individual lithologies are highest for USGS CW 81-2 core. Siltstone is the one exception to this pattern, because siltstone samples from USGS CE 82-1 have a slightly higher mean velocity. For compressional-wave velocities, there is an ordering of lithologies similar to that seen for other index and laboratory tests. Sandstone has the lowest velocity; siltstone, claystone, and carbonaceous claystone show a respective slight increase in velocity, yet can be generally grouped; coal has the highest velocity of the common lithologies. The velocities of the carbonate-cemented pebbly sandstone are substantially higher than any other material tested. A similar ordering based on shear-wave velocities exists except for the low velocities recorded for carbonaceous claystone. These lower shear-wave velocities are undoubtedly the result of the irregularly oriented positioning of coal lamina and stringers, which slow the propagation of the shear waves through the sample.

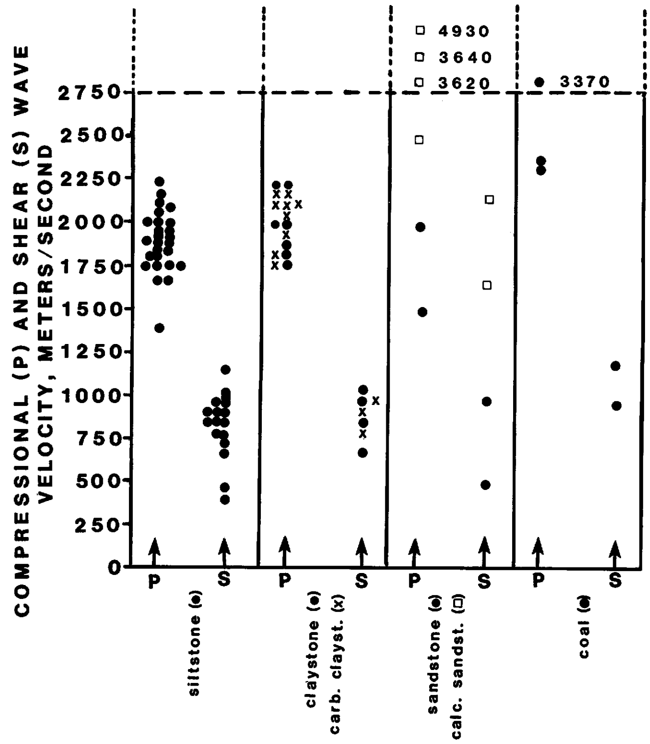

Figure 12. Distribution of ultrasonic compressional- and shear-wave velocity values for Chuitna coal field (USGS CW 81-2 and CE 82-1) core samples.

Compressional-Wave Velocity

Because of weathering, cementation, saturation, and expansion due to the removal of confining stresses during drilling, laboratory-derived velocities are often highly variable for near-surface earth materials. However, correlations and approximations between velocities and earth materials do exist and are useful if the physical conditions of the samples and their non-in-situ testing status are considered.

There is an empirical relationship between compressional-wave velocity and the quality or relative strength of most rocks and soil that was stated by Darracott (1976): "the greater the velocity the greater is their relative strength". He also infers that although rules of thumb may be misleading, one used for foundation studies in South Africa is: "Allowable bearing capacity = 300 kN/m^2 per 1,000 m/s of compressional velocity". Another comparison has been made between the economical dozing, ripping, and blasting characteristics (modified from the Caterpillar Tractor Co., 1972, by Miller, 1979) of rocks and seismic compressional-wave velocities (fig. 13). The bars shown on figure 13 correspond to the range of lithologic velocities of tested core samples of the Tyonek Formation. Velocities around 2,100 m/s are generally assumed to be the upper limit of economical ripping due to equipment wear and the necessity of additional crushing of large ripped blocks before removal.

Shear-Wave Velocity

In engineering studies, shear-wave velocity tends to have more potential applications than compressional-wave velocity but is considerably more difficult to measure. Shear-wave velocities are thought to be better indicators of lithology because shear-wave propagation is primarily controlled by the structural strength of the matrix and the size and strength of the grains, rather than by the degree of saturation (Whitely, 1983). While most classification schemes indicate that the dividing line between shear-wave velocity for soil (overburden) and that for firm compact soil is 600 m/s, the dividing line between firm soil and rock ranges from 765 to 1,800 m/s (Ohto and Shima, 1967, *in* Mooney, 1974; Murphy and others, 1979). The mean shear-wave velocities listed in table 5 for siltstone, claystone, carbonaceous claystone, and subbituminous coal fall within the above-cited transitional (soil to compact rock) velocity range. Thus, mean shear-wave velocities, as well as laboratory unconfined-compressive-strength means, characterize the majority of the unconfined lithologies of the Tyonek Formation as firm soil to soft rock.

Shearing strength is defined by the Coulomb equation (Terzaghi and Peck, 1967, p. 103) as shear strength at failure. For small structures on cohesive soils that are not drained when tested, shearing strength is proportional to about one-half of the unconfined compressive strength. Imai and Yoshimura (1975) have empirically related

Table 6. Ranges and means of compressional- and shear-wave velocity for specific lithologies from drill holes in the Chuitna coal field

[Arranged in order of increasing compressional-wave velocity. * indicates that samples were only available from drill hole CE 82-1; ** indicates that samples were only available from drill hole CW 81-2]

Lithology	Compressional Velocity (m/s)			Shear velocity (m/s)		
	Range	Number of samples tested	Mean	Range	Number of samples tested	Mean
DRILL HOLE CW 81-2						
Siltstone........	1681-2091	10	1875	685-975	5	821
Carbonaceous..... claystone.	1872-2232	7	2074	685-940	4	837
Claystone........	2014-2262	4	2154	916-989	4	958
Coal.............	2299-2350	3	2327	965-1050	2	1011
Calcareous....... sandstone.	2480-4827	4	3643	1678-2131	2	1905
DRILL HOLE CE 82-1						
Sandstone........	1474-1932	2	1703	435-945	2	690
Claystone........	1744-1880	3	1810	850-888	3	867
Carbonaceous..... claystone.	1762-1909	3	1822	705-736	3	724
Siltstone........	1659-2233	15	1927	654-975	13	845
Coal.............	All samples failed during compressional velocity testing.					
DRILL HOLES CW 81-2 AND CE 82-1 COMBINED						
Sandstone*.......	1474-1932	2	1703	435-945	2	690
Siltstone........	1659-2233	25	1908	654-975	18	838
Claystone........	1744-2262	7	2008	850-989	7	922
Carbonaceous..... claystone.	1762-2232	10	2123	685-940	8	794
Coal**...........	2299-2350	3	2327	965-1050	2	1011
Calcareous....... sandstone.*	2480-4827	4	3643	1678-2131	2	1905

shear-wave velocity for soil and relatively weak rocks to unconfined compressive strength. They have also reported relatively good correlations of in-situ shear-wave velocities in modern alluvial deposits and Tertiary strata with standard penetration "N" value (a measure of penetration resistance to a cylinder blade edge driven by a 61-kg hammer falling 76 cm).

Dynamic Poisson's Ratio and Elastic Moduli

If the compressional- and shear-wave-velocity ratio is measured, then Poisson's Ratio can be computed; if the bulk density is measured, then elastic moduli can also be computed. Neither soil nor rock are perfectly elastic and their strength characteristics can be quite different under static and dynamic loads. The dynamic load nearly always produces higher apparent strengths than does the static load. Both Coon and Merritt (1970) and Miller (1979) have compared laboratory (ultrasonic) dynamic measurements on intact core with in-situ dynamic measurements. They have reported a bias (in many cases, forced by core quality) for laboratory measurements toward selecting intact samples, whereas the in-situ measurements will include discontinuities and weak zones. Larkin and Taylor (1979) have also compared shear moduli obtained from their downhole measurements on relatively low strength rocks to those obtained from laboratory measurements on the same rocks. They found that the inhole shear moduli were linear only for strain less than about 10^{-5} cm/cm. They also found that the laboratory-derived moduli agreed approximately with the inhole moduli in the range of relative low strain but that the laboratory moduli decreased considerably as the strain was increased.

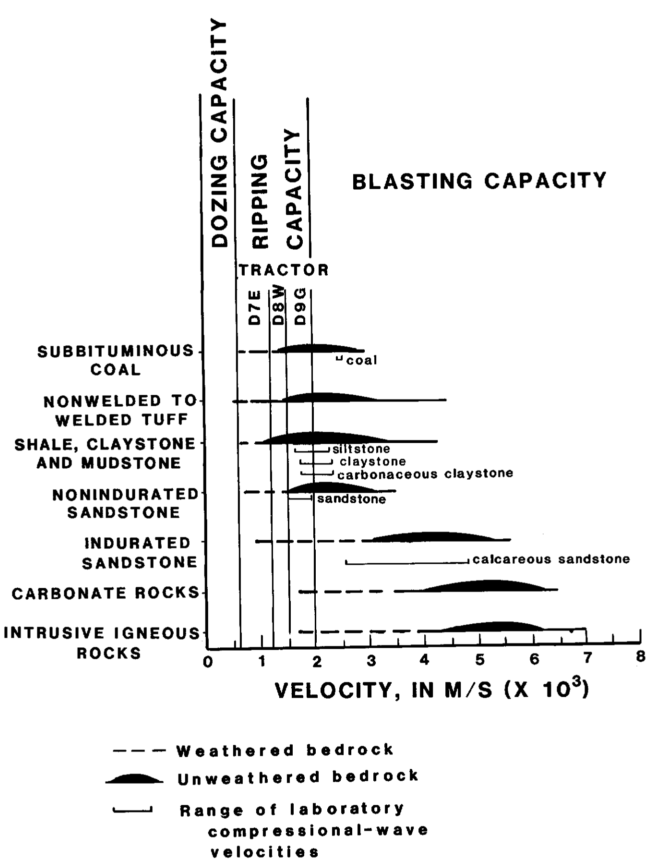

Figure 13. Compressional-wave velocities and estimated dozing, ripping, and blasting capabilities of various rock types. Data are taken from surface measurements in the Powder River basin, Wyoming (literature and estimates). The rippability chart was modified from the Caterpillar Tractor Co. (1972) by Miller (1979).

Table 7 presents average values for Poisson's ratio and the dynamic elastic moduli (shear, Young's, and bulk) for the lithologies that were found in the core of the Tyonek Formation. The dynamic elastic moduli that are presented in table 7 were computed from mean compressional- and shear-wave velocity data (table 6) and mean bulk density values from the selected core samples that were tested on laboratory ultrasonic equipment that generated high loading rates at low-strain levels. These dynamic elastic moduli are undoubtedly higher than in-situ measured moduli would be.

GEOPHYSICAL LOGGING AND GROUND WATER

Continuous natural gamma radiation, gamma-gamma radiation, neutron radiation, hole diameter, spontaneous potential, single-point resistance, and temperature measurements were obtained by logging the four holes soon after the completion of drilling. Single-point resistance and spontaneous potential logs were not obtained in drill hole USGS CE 82-1 due to hole collapse following casing removal (Odum and others, 1986). A Well Reconnaissance Geologger[2] with single-conductor cable was used following the techniques described by Keys and MacCary (1971).

The geophysical-log responses document most major lithologic contacts. In general, interpretations of the suite of logs reinforce the subtle differences noted on the lithologic logs (Odum, 1986). This summary consists of excerpts of the more noteworthy observations and interpretations that were previously published in reports on each individual drill hole (Chleborad and others, 1980, 1982; Odum and others, 1983, 1986).

Capps Coal Field

Drill Hole USGS 1C-79

The temperature log, which was run inside the drill stem after the hole was allowed to stabilize for 20 hr, indicated a temperature gradient of approximately 1.6 °C/100 m for the measured interval of 40.8–118 m. In that interval, the temperature ranged from 4.1 °C at 40.8 m to 5.1 °C at 118 m. The gradient is low relative to typical gradients of 1.8–2.4 °C/100 m seen outside the Cook Inlet area but is similar to that measured in an unsuccessful oil well near Anchorage (Keys and MacCary, 1971), where the low-temperature gradients were attributed to significant ground-water circulation.

The anomalous rise in temperature at 118.7 m occurs near the top of the Waterfall coal bed. The heat source is possibly an exothermic reaction in the coal caused by frictional forces generated in the drilling process. High drilling pressure was applied at that depth (119 m) in an effort to core the coal, with what was later determined to be a badly worn bit. Some of the retrieved sample was badly broken and smelled like creosote and hydrogen sulfide. The temperature probe was raised and lowered several times to check the validity of the local heat source and then left stationary at the 118.7-m level (the bottom of the hole) for about 2 hr. A maximum temperature of 10.7 °C was recorded at the end of the 2-hr period (Chleborad and others, 1980).

The following descriptions of the hydrologic conditions are based on information obtained from a 76-m-deep test hole 30 m south of drill hole 1C-79 (G.L. Nelson, written commun., 1979). The materials were unsaturated to the total depth except for a few thin perched-water-table zones. Only the perched-water-table zone at 9.1 m yielded any measurable water (about 2 L/min). A little seepage was detected between 40.8 and 41.4 m, but the zone between 60.9 and 76.2 m is quite permeable. The

[2]Any use of trade names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Table 7. Average ultrasonic velocities, bulk densities, and calculated Poisson's ratio and dynamic elastic moduli for the Tyonek Formation

Lithology	Bulk Density (g/cm³)	Compressional Velocity (m/s)	Shear Velocity (m/s)	Poisson's Ratio	Shear Modulus (N/m²)	Young's Modulus (N/m²)	Bulk Modulus (N/m²)
Sandstone	2.13	1703	690	0.402	7.4×10^{8}	2.1×10^{9}	5.2×10^{9}
Siltstone	2.01	1908	838	.381	1.4×10^{9}	3.9×10^{9}	5.4×10^{9}
Claystone	1.96	2008	922	.363	1.7×10^{9}	4.6×10^{9}	5.6×10^{9}
Carb. Clayst.	2.07	2123	794	.419	1.3×10^{9}	3.7×10^{9}	7.6×10^{9}
Coal	1.15	2327	1008	.384	1.2×10^{9}	3.3×10^{9}	4.7×10^{9}
Calc. Sandst.	2.55	3643	1904	.312	9.3×10^{9}	2.4×10^{10}	2.2×10^{10}

perched-water-table zone at 9.1 m corresponds to the contact between the surficial diamicton and the underlying claystone, which indicates that the claystone is an aquiclude that inhibits the downward migration of water. The seepage detected between 40.8 and 41.4 m corresponds to the upper part of the Capps coal bed and the base of the carbonaceous claystone above. The permeable zone between 60.9 and 76.2 m corresponds to what is mostly a nonrecovery zone believed to be composed of friable sandstone. The only direct indication of hydrologic conditions between 76.2 and 121 m comes from drill hole 1C–79 where circulation of drilling fluid was never attained, which indicates downward continuation of the unsaturated permeable material.

Drill Hole USGS 2C–80

All coal beds within the logged interval, except for a very thin bed at 40.2 m, caused conspicuous deflections on the radiation logs. These responses were the result of a very low natural-gamma radiation level, a low backscatter level on the neutron log because of the abundance of hydrogen molecules, and relatively low density indicated by a marked increase in the gamma-gamma count rate.

The suite of geophysical logs, especially the natural-gamma and electric logs, strongly indicate that beds below 47.2 m, for which no core was retrieved, are probably composed of relatively clean granular material—most likely medium- or coarse-grained sandstones. The highly sensitive and finely calibrated thermistor-type probe detected a rapid temperature increase of over 0.5 °C below 49.7 m. A warmer, nearly constant temperature of 3.3 °C occurred below 50.3 m.

Chuitna Coal Field

Drill Hole USGS CW 81–2

The suite of seven geophysical logs were run under flowing artesian conditions of 15–19 L/min, and the only casing in the hole was an 11-cm (inside diameter) steel casing that extended to 7.6 m below the ground surface. The initial depth of geophysical logging, 98.5 m, was about 3.5 m less than the final depth of drilling, 102 m, due to accumulations of caved material. During the logging process, the hole continued to fill slowly with debris from the walls.

Two conspicious lithologic units are evident on the log suite: a very competent, dense, low-porosity, carbonate-cemented pebbly sandstone bed from 50.0 to 51.1 m; and a hard tuffaceous(?) bed from 85.9 to 86.1 m. The dense nature of the carbonate-cemented bed was strongly reflected on all logs except the spontaneous potential and temperature logs. The fact that this bed withstood significant hole caving, both above and below itself as shown by the caliper log, is evidence of its competence. Although cemented sandstones are commonly not thought of as aquicludes, this bed, if it has much lateral continuity, may severely restrict vertical ground-water movement.

The tuffaceous(?) bed caused significant responses on three logs as follows: (1) Low natural-gamma spike, (2) high electrical-resistance spike, and (3) high density-gamma-gamma spike. The lack of diagnostic character on the neutron log is probably due to the relatively large sphere of radiation influence with respect to the thinness of the bed, whereas the smaller sphere of influence of the other radiation logs allowed detection of this bed.

The two thickest intervals (43.1–50.0 m and 51.1–55.5 m), for which no core was recovered, have similar geophysical log responses. This suggests that these two intervals are composed of moderately well sorted, weakly lithified sandstone. The caliper log clearly shows that the material is highly susceptible to caving. Therefore, it seems logical to conclude that the porosity, and probably the permeability, of these beds is substantially greater than that of the carbonate-cemented sandstone bed that was cored at 50 m.

The drill-hole-fluid temperature log is the most valuable log of the suite for the delineation of the ground-water system. Ground water moving through porous or fractured rocks within about 100 m of the surface may be expected to keep those permeable beds (aquifers) cooler than impermeable beds (aquicludes). This phenomenon is thought to occur because the average annual temperature of recharging water is less than that of subsurface rocks that are not subjected to ground-water circulation. The aquiclude, instead, retains more geothermal heat. The interface between relatively permeable and relatively nonpermeable beds is, therefore, commonly a zone of significant temperature change. This change takes the form of an increase of temperature as the probe's sensor is lowered past the bottom of an aquifer and into an aquiclude. The magnitude of decrease on the temperature log, when it is in an aquifer, is commonly proportional to the volume of water that enters the hole at that point.

The temperature log shows three depths where temperatures in the drill hole rise significantly. A 0.4 °C increase occurs within the top half of the upper coal bed at approximately 19.8 m, a similar more abrupt rise within the same coal bed is at about 26 m, and a rise of 1.3 °C occurs at 73.6 m at the bottom of the middle coal sequence.

Drill Hole USGS CE 82–1

A suite of five borehole geophysical logs was recorded for this drill hole, starting 15 hr after drilling ended. Following five logging runs, the casing was pulled upward in an attempt to expose more of the upper section for electric logging. However, the loose, sandy unit above 15 m, identified from the gamma-gamma and lithologic log (fig. 5*D*), collapsed into the hole. Even during the 8 hr of logging, material caving from below the casing reduced the hole depth by approximately 4 m. This rate of filling by natural caving was greater than that which occurred in the other three core holes.

The neutron log normally reflects the variation of "total porosity" of the saturated earth materials. This log indicates that the sandstone unit between 44.8 and 57.2 m has the least saturated porosity of the geologic units in this hole, although log interpretations are complicated by hole enlargement. This interpretation agrees with logging observations for other holes in the area (Chleborad and others, 1980, 1982; Odum and others, 1983, 1986).

The gravelly zone between 52.9 and 55.8 m is characterized as being a moderately firm, cemented sandy gravel, and higher density and lower prorsity is indicated by the radiation logs. The gamma-gamma response indicates that material in this zone has the highest bulk density found in this hole.

A bowing in the temperature profile is observable opposite the upper coal bed, followed downhole by a gentle decline in borehole temperature in the underlying sandstones and siltstones. Because the area's ground-water flow system has not been defined, any explanation of the bowing phenomenon is speculative. An alternative to a hydrothermal cause is that enough oxygen-rich drilling water may have been lost to the coal to produce detectable heat from slight oxidation. Two sharp spikes of about 0.22 °C were recorded at 75.3 and 108.2 m. The sudden increase in temperature at 75.3 m seemingly correlates with the most pronounced hole enlargement recorded on the caliper log. Although perhaps coincidental, the geotechnical log mentions slickensides at 75.9 m in a moderately thick, firm to very firm siltstone. Ground water, slightly warmer than its surrounding environment, is believed to be entering the borehole from a thin, presumably fractured zone. This inflow and temperature anomaly could result from a depressed water level in the borehole after drilling ceased that had not risen to stabilization (static level) at the time of logging.

The temperature spike at 108.2 m could not be explained by observing the other logs. The radiation and caliper logs do not indicate a zone of weakness here. If the temperature "blip" is real, fractures too narrow for the probes to detect must be present.

CONCLUSIONS

The Tyonek Formation of early Oligocene through middle Miocene age is a nonmarine sequence of sandstone, siltstone, claystone, carbonaceous claystone, coal, and lignite, all deposited in a poorly drained alluvial basin. Distribution histograms showing the relative abundance of various lithologies indicate that drill holes in the Chuitna coal field have a higher percentage of fine-grained rock units than the drill holes in the Capps coal field. This difference in lithologic character may reflect a higher energy basin-margin environment for the Capps field location as opposed to a lower energy, more basinward setting of the Chuitna field, or it may reflect a basin-wide change in depositional energy in response to a slowing of basin margin uplift and (or) a slowing of basin subsidence during early and middle Miocene time.

A suite of geophysical logs that were run in each drill hole proved to be invaluable in interpreting the lithology of unrecoverable intervals, which were mainly composed of weakly lithified sandstone. The log suites also provided independent confirmation of the existence of practically all major lithologic contacts. Based on this experience, geophysical logging could be substituted for continuous coring in some areas, with little loss in reliability of identifying significant geologic units.

The geophysical log suites provided useful information on ground-water conditions. Drill-hole fluid-temperature profiles were especially interesting because they delineated specific depth intervals where ground water was either entering or exiting the drill hole. However, the typical 20 hr that were allowed for thermal equilibration after the completion of drilling may have been insufficient for temperature logging of normal ground-water flow in holes USGS 1C–79 and 2C–80, especially if an exothermic reaction in the coal was generated by excessive bit friction. Regardless of the origin, thermal anomalies recorded on the temperature logs identified zones of fractured coal or poorly lithified sandstone that were substantially more permeable.

In general, the range and mean values derived from the field and laboratory tests, along with distinctive similarities in drill hole geophysical logs, indicate that there is little difference in the physical character of specific lithologies between the two coal field areas. The hardness classification of most of the lithologies of the Tyonek Formation ranges from stiff soil to soft rock. Test-result ranges of slake-durability index, point-load strength index, unconfined compressive strength, and ultrasonic velocities vary widely for a specific lithology. However, on the basis of computed means of the above properties, the lithologies within a given drill hole or coal field area can be arranged in the following order of increasing strength and durability: weakly lithified sandstone, siltstone, claystone, carbonaceous claystone, and coal. From this order, there appears to be a rough correlation between a decrease in overall grain-size content and an relative increase in physical strength and durability. This relationship suggests that the clay particles are acting as a weak cementing agent when other agents such as carbonate, oxides, and silica, are, for all practical purposes, absent.

The inherently nonhomogeneous nature of many of these lithologies of the Tyonek Formation causes difficulty in testing, interpreting individual test results, and ultimately, characterizing a lithologic unit within the formation. Thin laminae of micaceous minerals cause zones of weakness that may produce significantly diverse test results for samples that are similar in appearance.

Because the majority of the sandstone units of the Tyonek Formation were essentially nonrecoverable due to their nonlithified character, an arrangement of the lithologies into three groups may be more realistic. For most purposes, sandstone can be considered to have zero unconfined strength and durability, and therefore may present some slope stability problems during construction. Siltstone, claystone, and carbonaceous claystone all have low to moderate strength and durability depending on clay-particle content, size, and orientation and on quantity of micaceous and carbonaceous inclusions. The coal units have unconfined strengths at least twice those of the finer grained lithologies. The rare carbonate-cemented pebbly sandstone unit has a strength and durability anomalously higher than all other lithologies. If, during construction, these carbonate-cemented units were found to be thicker, to occur in larger quantity, and (or) to have relatively large lateral extent, they definitely would be of engineering significance.

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