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DEPARTMENT OF THE INTERIOR
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TEXTURAL AND MINERALOGICAL STUDY OF SANDSTONES FROM THE ONSHORE GULF OF ALASKA TERTIARY PROVINCE, SOUTHERN ALASKA

By
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This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature.

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ABSTRACT

Petrographic examination of 74 outcrop samples of Paleocene through Pliocene age from the onshore Gulf of Alaska Tertiary Province indicates that sandstones of the province characteristically are texturally immature and mineralogically unstable. Diagenetic alteration of framework grains throughout the stratigraphic sequence has produced widespread zeolite cement or phyllosilicate grain coatings and pseudomatrix. Multiple deformation and deep burial of the older Tertiary sequence--the Orca Group, the shale of Haydon Peak, and the Kulthieth and Tokun Formations--caused extensive alteration and grain interpenetration, resulting in low porosity values. Less intense deformation and intermediate depth of burial of the younger Tertiary sequence--the Katalla, Poul Creek, Redwood, and Yakataga Formations--has resulted in a greater range in textural properties. Most sandstone samples in the younger Tertiary sequence are poorly sorted, tightly packed, and have strongly appressed framework grains, but some are less tightly packed and contain less matrix. Soft and mineralogically unstable framework grains have undergone considerable alteration, reducing pore space even in the youngest rocks.

Measurements of porosity, permeability, grain density, and sonic velocity of outcrop samples of the younger Tertiary sequence indicate a modest up-section improvement in sandstone reservoir characteristics. Nonetheless porosity and permeability values typically are below 16 percent and 15 millidarcies respectively and grain densities are consistently high, about 2.7 gm/cc. Low permeability and porosity values, and

high grain densities and sonic velocities appear to be typical of most outcrop areas throughout the onshore Gulf of Alaska Tertiary Province.

INTRODUCTION

Evaluation (or re-evaluation) of potential petroleum resources of the Gulf of Alaska Tertiary Province (GATP) is intensifying in anticipation of lease sales on the outer continental shelf. A recent report by Plafker, Bruns, and Page (1975) summarizes the status of publicly available geological data and emphasizes the critical importance of sandstones with suitable reservoir qualities for the petroleum potential of the GATP outer continental shelf. Although geological maps at a scale of 1:125,000 or larger are available for much of the onshore area (Miller, 1957, 1971, 1975; Plafker and Miller, 1957; Winkler, 1973; Plafker, 1974), little detailed information has been published on characteristics of the Tertiary sedimentary sequences in general, and of the sandstones in particular. This report presents qualitative and quantitative textural and mineralogical data for 74 sandstone samples from various localities in the onshore part of the GATP (fig. 1) and should facilitate forecasting physical properties of the offshore sedimentary rocks.

Samples analyzed in this study were collected from 1963 to 1972 in conjunction with regional geological mapping and measurement of stratigraphic sections at key locations by Plafker and Winkler. All samples are from surface outcrops. The majority are from measured sections,

STRATIGRAPHIC SECTIONS

Solid where measured, dashed where estimated from aerial photos. Numbers on right side of columns are samples with packing density, porosity, permeability, grain density, and some sonic velocity measurements; numbers on left are those with mineralogical data.

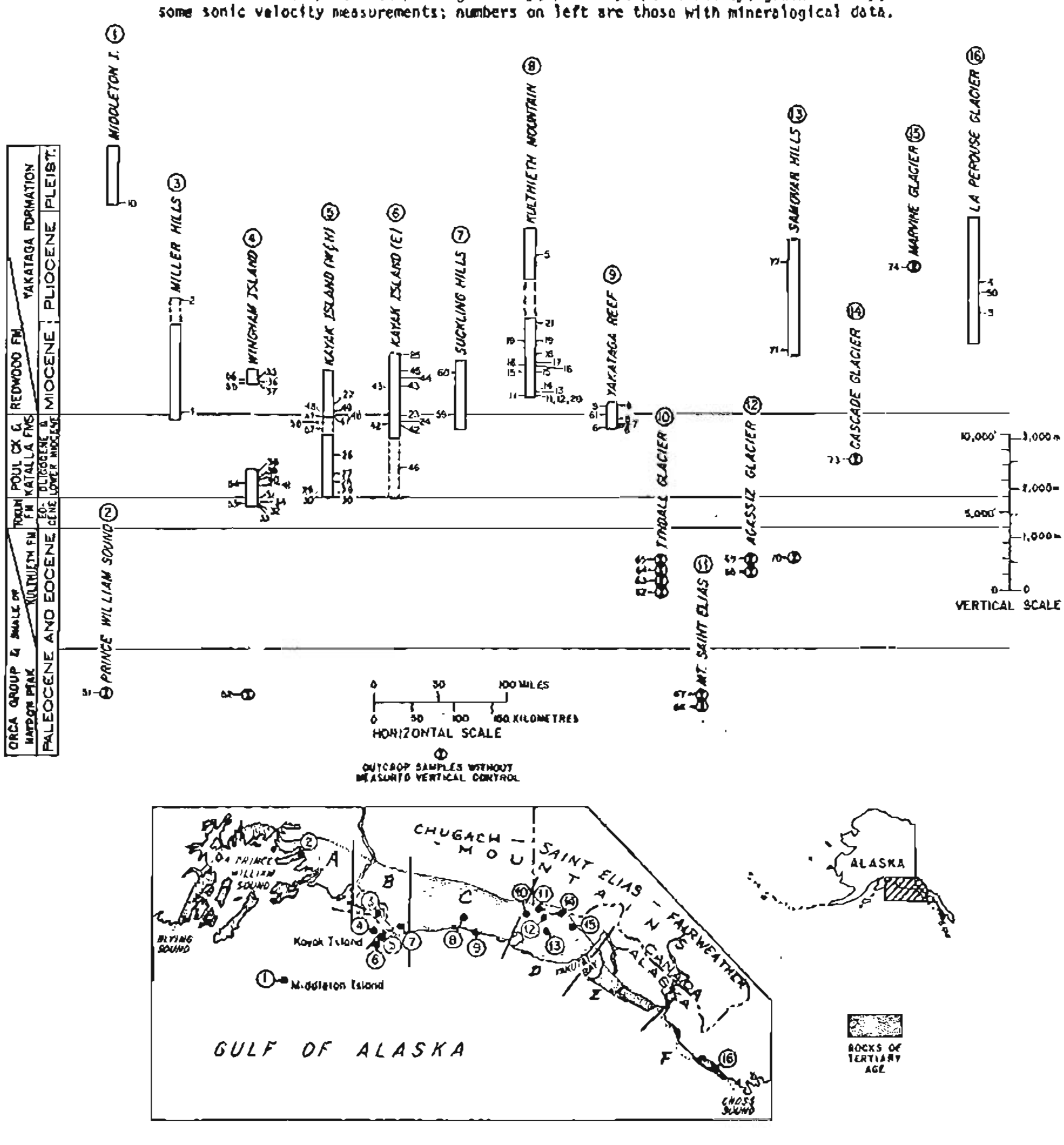


FIGURE 1. LOCATION MAP AND STRATIGRAPHIC RELATIONS OF ANALYZED SANDSTONES FROM THE ONSHORE GULF OF ALASKA TERTIARY PROVINCE

Districts: A, Prince William Sound; B, Katalla; C, Yakataga; D, Malaspina; E, Yakutat; F, Lituya and thus their relative stratigraphic positions are well known (fig. 1). Many samples, however, were collected at isolated outcrops; their formation assignment is reliable but their relative stratigraphic positions are uncertain. The samples are from the Lituya, Malaspina, Yakataga, Katalla, and Prince William Sound districts, and from Middleton Island (fig. 1). Although samples were collected from the entire Tertiary section, most analyses of physical properties were made on sandstones from the upper part of the section--the Katalla, Poul Creek, and Yakataga Formations--since possible horizons of petroleum accumulation offshore are in these units.

Textural Characteristics of the samples were studied in three ways: (1) by examination of slab samples with the binocular microscope; (2) by estimation and then measurement of sorting, packing density, and percent matrix in thin sections with the petrographic microscope; and (3) by laboratory measurement of permeability, porosity, grain density, and sonic velocity in plugs. Mineralogical characteristics were studied by modal analyses of thin sections that had been stained for potash feldspar and impregnated with dyed plastic to enhance open pores, and by x-ray diffraction of whole rock samples and mineral separations.

STRATIGRAPHIC AND STRUCTURAL SETTING

The Gulf of Alaska Tertiary Province (Plafker, 1967, 1971) includes an onshore area of approximately 29,000 km^2 (11,000 mi^2), extending from near Cross Sound on the east to Blying Sound on the west. The province is underlain by a thick sequence of marine and nonmarine sedimentary and volcanic rocks that range in age from Paleocene through Pliocene (and locally Pleistocene). Tertiary and Quaternary strata also extend offshore under much of the contiguous continental shelf, perhaps an additional 52,000 km^2 (20,000 mi^2).

Systematic surface mapping of the province has been carried out intermittently since 1944 as part of the U. S. Geological Survey petroleum investigations in southern Alaska. Additional information on the province has come from geophysical studies and from 26 deep exploratory wells and many core holes drilled along the coastal lowlands that border the Gulf of Alaska. The geology and petroleum potential of the GATP has been described in a series of Geological Survey reports and maps and has been summarized recently by Plafker (1971) and Plafker, Bruns, and Page (1975) in papers that contain extensive lists of source data. The following outline of the geologic setting of sequences that were sampled for the present study was modified from these two publications. The interested reader is referred to them for additional information on the geology of the GATP.

Tertiary strata of the province are broadly divisible, on the basis of structural style, into two terranes: (1) an older sequence of well indurated, complexly deformed rocks of early Tertiary age (Paleocene and Eocene); and (2) a younger sequence, mainly of middle and late Tertiary age, that is considerably less indurated and deformed.

The older Tertiary sequence, which consists of the Orca Group, the shale of Haydon Peak, and the Kulthieth and Tokun Formations, is mainly flyschlike bathyal marine sedimentary rocks interbedded with mafic volcanic rocks in the Prince William Sound and western Katalla districts (Winkler, 1976; Plafker, 1974) and shallower marine and continental sedimentary rocks with abundant coal in the eastern Katalla, sedimentary rocks with abundant coal in the eastern Katalla, Yakataga, and western Malaspina districts (Plafker, 1971). West of the Katalla district, the upper part of the older sequence is not present; to the east, the lower part thins and was deposited at progressively shallower depths. East of Yakutat Bay, the lower part of the older sequence is not present. The maximum thickness of the older Tertiary sequence is estimated to be at least 7000 m (23,000 ft), but prevailing structural complexity and lack of lithologically distinctive beds preclude reliable measurements.

The younger Tertiary sequence, which consists of the Katalla, Poul Creek, Redwood, and Yakataga Formations, is mainly bathyal to littoral marine mudstone, siltstone, and subordinate sandstone. Its lower part is characterized by organic-rich strata, glauconitic sandstone, and lesser tuff, agglomerate, and pillow lava; and its upper part by abundant glaciomarine detritus (Plafker, 1971; Miller, 1951, 1975). Faunal types in the younger Tertiary rocks indicate a progressive cooling from subtropical and paratropical climatic conditions that prevailed during deposition of the lower part of the younger sequence to cold water conditions that have prevailed from mid-Miocene to the present time. Thicknesses of the younger Tertiary units vary greatly from place to place, but an average composite thickness is on the order of

6100-7600 m (20,000-25,000 ft).

Deformation of varying intensity has affected the GATP throughout much of Cenozoic time, but the most intense orogenic episodes culminated in early and late Tertiary time (Plafker, 1969). Older Tertiary rocks that have been involved in both major orogenies are markedly more deformed than, and locally differ in structural trends from, the younger Tertiary sequence. The early Tertiary orogeny probably had two phases that culminated in Eocene time: (1) an earlier phase of complex tight folding and pervasive faulting, generally trending parallel to the present continental margin, while the lower Tertiary rocks were only semilithified and still contained considerable amounts of pore water; and (2) a later phase of extensive emplacement of 50 m. y. old granitic plutons (Plafker and Lanphere, 1974) that in some places have broad discordant thermal aureoles. These two phases, which were separated by perhaps 5-10 m. y., resulted in regional metamorphism of the lower Tertiary rocks to the zeolite, and locally the prehnite-pumpellyite, facies (Winkler and Plafker, 1974).

The younger orogeny, which began by early Miocene time east of the Copper River, resulted in pronounced differential uplift of the Chugach, Saint Elias, and Fairweather Mountains, and asymmetric folding and thrusting of older sequences over younger along a series of major east- to northeast-trending imbricated faults (Plafker, 1969). There is a general decrease in the intensity of folding and the magnitude of fault displacements from north to south across the onshore GATP; fold asymmetry and fold and fault orientations indicate NW-SE compressive stress. Minor unconformities and thick beds of conglomerate in the lower part of the younger Tertiary sequence onshore indicate local uplift and erosion in early Miocene time. Multiple angular unconformities in the upper part of the younger Tertiary sequence indicate that structures were growing during late Pliocene time. Abundant glaciomarine detritus throughout the younger Tertiary sequence attests to a structurally positive northern margin to the basin sufficiently mountainous to nourish tidewater glaciers (Plafker, Bruns, and Page, 1975). Preliminary interpretations of seismic reflection profiles of part of the offshore GATP (Bruns and Plafker, 1975) suggest that the onshore structural style in general extends onto the outer continental shelf, although structures offshore may be more open. Shallow earthquake foci on the shelf in addition to tilting, faulting, and uplift of marine rocks as young as middle Pleistocene on the Middleton Island platform indicate that some of the offshore structures also are growing actively.

TEXTURE

The sandstone samples were collected from a variety of bed types, including thin and lenticular strata, massive and continuous strata, poorly sorted and altered beds, and clean and fresh beds. Inasmuch as the samples were collected with overall formational characteristics in mind rather than for optimum reservoir potential, we judge it preferable to evaluate textural properties by stratigraphic unit. Descriptions and field relations of individual samples are listed in Appendix 1.

Figure 2 shows correlation of stratigraphic units with six sandstone textural properties: (1) sorting, (2) packing density (estimated and measured), (3) type of grain contacts, (4) cementing agent, (5) percent of matrix, and (6) proportion of altered samples. The data from which this figure has been constructed are included in Appendices 2 and 3. Within each textural category, we arbitrarily have ranked properties so that, in most cases, more favorable characteristics for reservoir potential are to the right side of the abscissa and less favorable are to the left. The ordinate in all cases is the percent of total samples that exhibit the particular properties.

(1) Sorting was estimated visually by referring to sorting images illustrated in Pettijohn, Potter, and Siever (1972, p. 585).

(2A) Estimated packing density was determined visually where

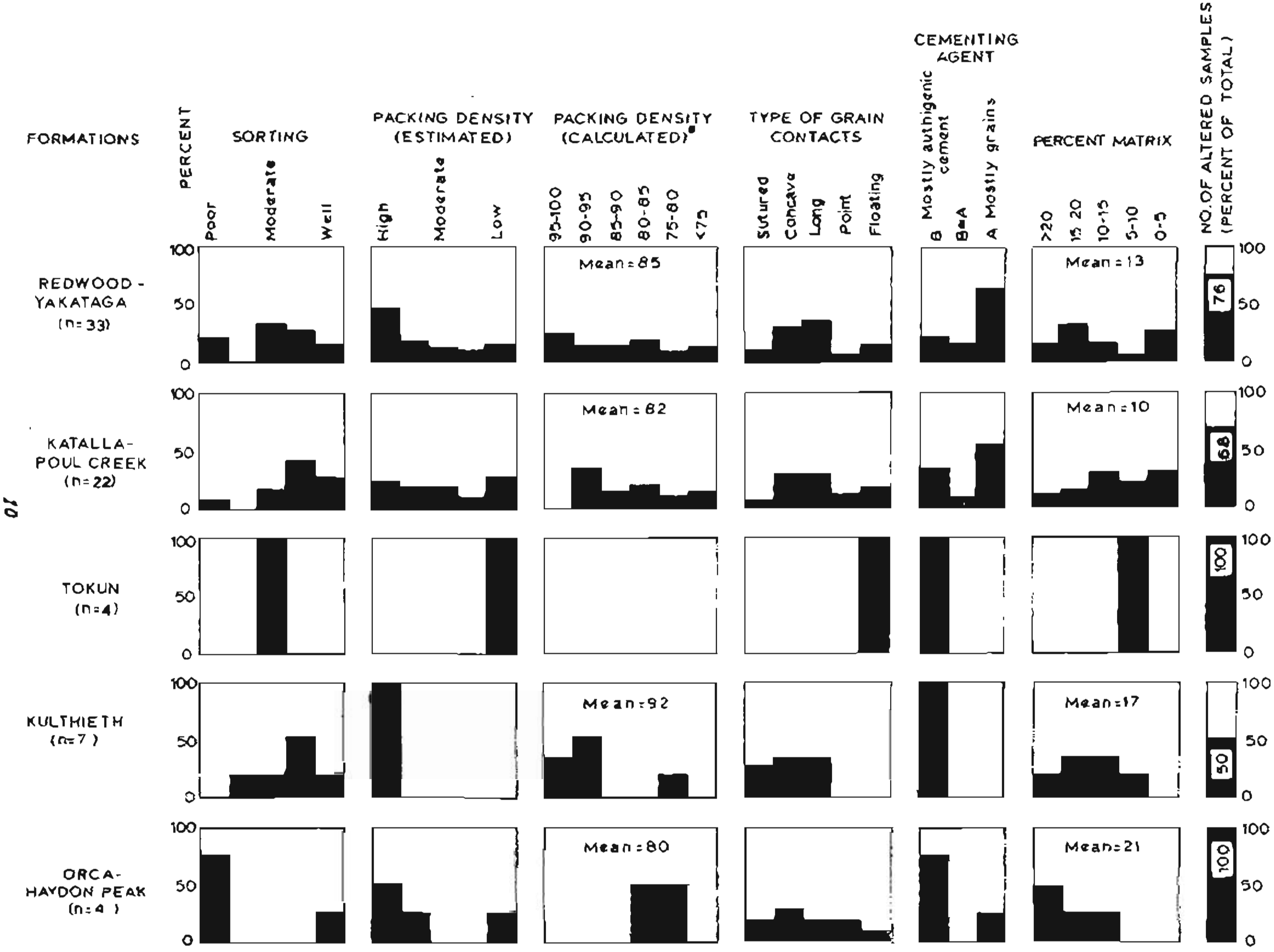
High = framework grains tightly packed with abundant interpenetration involving squeezing of relatively soft lithic fragments between and around more resistant grains such as quartz and feldspar;

Moderate = closely packed framework with minor grain interpenetration and little or no deformation of lithic fragments; and

Low = framework separated by or "floating" in matrix or authigenic cement with no observable grain interpenetration.

(2B) Calculated packing density was measured by the formula,

Packing density ≈ pd = $\frac{m \sum_{i=1}^{n} g_i}{t} \times 100$, where g_i represents the grain-



* Not calculated if abundant carbonate is present

FIGURE 2. HISTOGRAMS OF SELECTED TEXTURAL PROPERTIES OF 70 SANDSTONES, GULF OF ALASKA TERTIARY PROVINCE (n=number of samples)

intercept size of the ith grain, r_i, of a traverse of n grains of absolute length, t, where m = a magnification correction (Kahn, 1956). A high value of pd indicates a very tightly packed framework with little pore space or matrix. In these samples, pd was not measured where authigenic carbonate was estimated visually to be more abundant than 25 percent of the thin section.

(3) Type of grain contacts (Taylor, 1950) include a) sutured grains, mutual stylolitic interpenetration of two or more grains (which must be distinguished carefully from grains of polycrystalline quartz), usually attributed to much pressure solution; b) concavo-convex grain contacts, usually attributed to moderate pressure solution; c) long or straight contacts, indicative of only minor compaction and pressure solution; d) point or tangential contacts, minor or no pressure solution; and e) floating grains which are not in contact with other framework constituents. Inasmuch as most samples exhibit more than one type of common grain contact, these histograms total more than 100 percent.

(4) Cementing agent is separated into three categories: grains mostly bound together by authigenic cement (carbonate, zeolite, or clay minerals), grains mostly interpenetrative, or subequal proportions of cement and appressed grain boundaries.

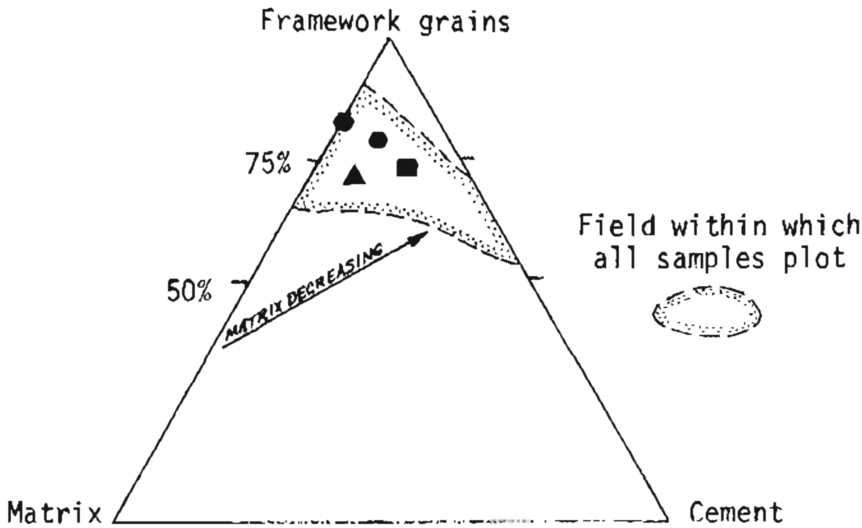
(5) Percent of matrix is a rather subjective index that may include intergranular material of diverse origin. In sandstones such as these with moderate to advanced framework alteration and ubiquitous phyllosilicate coatings and pore filling, it may be nearly impossible to distinguish original matrix from altered rock fragments or pseudomatrix.

This problem is discussed by Dickinson (1970). Certainly several types of clayey matrix (lutem) occur in these sandstones; since their influence on ultimate rock texture is the same, they have been combined for this diagram.

(6)Number of altered samples depicts the percentage of total samples for each stratigraphic unit that exhibit widespread alteration of framework grains (chiefly alteration of lithic and feldspar grains).

There is an obvious interrelationship of textural properties which we interpret as having an important affect on sandstone reservoir quality. For example, there should be a good inverse correlation between packing density and percentage of cement or matrix in each sample. It is possible, however, to get anomalously high matrix counts in tightly compacted rocks that contain badly squeezed aphanitic lithic fragments because the fragments may be mistaken for lutem. This is particularly likely when framework grains have been altered. Packing density also normally will be related indirectly to the type of grain contacts, as will porosity and, possibly, cement. Tightly appressed grains with sutured, concavo-convex, and long contacts usually occur in sandstones with a high packing density and low porosity, unless fracture porosity is present. Interstitial cement, if present at all, usually consists of silica overgrowths with only minor carbonate or clay.

Interrelations of the textural components, framework, matrix, and cement (fig. 3), lead us to believe that most of these sandstones were relatively clean (primary matrix less than 15 percent) when deposited and could have permitted early migration of hydrocarbons prior to



FORMATIONS		Components					
		FRAMEWORK		MATRIX		CEMENT	
		Mean	(Range)	Mean	(Range)	Mean	(Range)
●	Yakataga-Redwood (n=14)	79	(55-89)	13	(2-24)	8	(0-44)
■	Katalla-Poul Creek (n=10)	73	(33-88)	10	(2-24)	16	(0-58)
⬢	Kulthieth (n=8)	83	(75-89)	17	(11-25)	0	(0-0.5)
▲	Orca-Haydon Peak (n=4)	72	(65-85)	21	(13-34)	7	(1-16)

Figure 3. Textural components of 36 sandstones, Gulf of Alaska Tertiary Province (n=number of samples).

porosity reduction by compaction, alteration of framework grains, and formation of authigenic cement and matrix. We should emphasize that these diagenetic changes may have begun early in the post-depositional history of the sandstones. Rapid sedimentary burial and coeval tectonism have occurred during much of Cenozoic time in the eastern Gulf of Alaska--conditions which may have led to rapid reduction of original porosity and permeability.

Important differences in textural properties between the lower Tertiary and the middle and upper Tertiary rocks reflect the intense deformation of the older rocks. The Orca, Haydon Peak, and Kulthieth samples usually have strongly interpenetrated grains; where grains are not as strongly appressed, they are surrounded by pseudomatrix. The dominant matrix minerals are quartz, sericite, and laumontite. Quartz coatings on grains are present frequently; clay coatings are infrequent. Prehnite occasionally is present in veins or patches. In general, prehnite is more typical of the Orca Group and laumontite and authigenic quartz of the Kulthieth Formation.

The middle and upper Tertiary rocks have more diverse textural properties than those in the lower Tertiary section. Generally the Tokun, Katalla, Poul Creek, Redwood, and Yakataga Formations tend to be better sorted and less tightly compacted, with less pressure solution and pseudomatrix. Where matrix is abundant, it tends to be a primary admixture, although commonly chlorite and sericite, and occasionally laumontite, are present as matrix minerals. Carbonate cement is very common, and glauconite, both as interstitial material and as discrete grains, occurs frequently. Surprisingly each of the middle and upper Tertiary formations also has dense, thoroughly altered samples with strong interpenetration of framework grains. Thus, middle and upper Tertiary formations have representatives in almost every textural category (fig. 2).

As indicated in figure 3, the mean proportion of matrix for each stratigraphic unit decreases with decreasing age (and decreasing potential depth of burial), except that the Yakataga Formation has a slight increase in primary matrix. This further supports our concept that most of the matrix in sandstones from the Gulf of Alaska Tertiary Province is derived secondarily.

PERMEABILITY, POROSITY, GRAIN DENSITY, AND SONIC VELOCITY

Measurements of air permeability, porosity, and grain density were made by Core Laboratories, Inc., of Dallas, Texas, on 50 sandstone samples from the GATP. In addition, sonic velocities at six different effective overburden pressures were measured on 25 of these samples from small cylindrical plugs that were saturated with a brine containing 30,000 parts per million sodium chloride. Complete data are listed in Appendices 4 and 5. Permeability is compared with relative stratigraphic positions of the analyzed samples on figure 4. Porosity, grain density, and sonic velocity with respect to stratigraphic position are depicted on figure 5.

Measured permeabilities in the entire sample suite are low, with a mean of 3.8 millidarcies (Md) but a median value of only 0.08 Md.

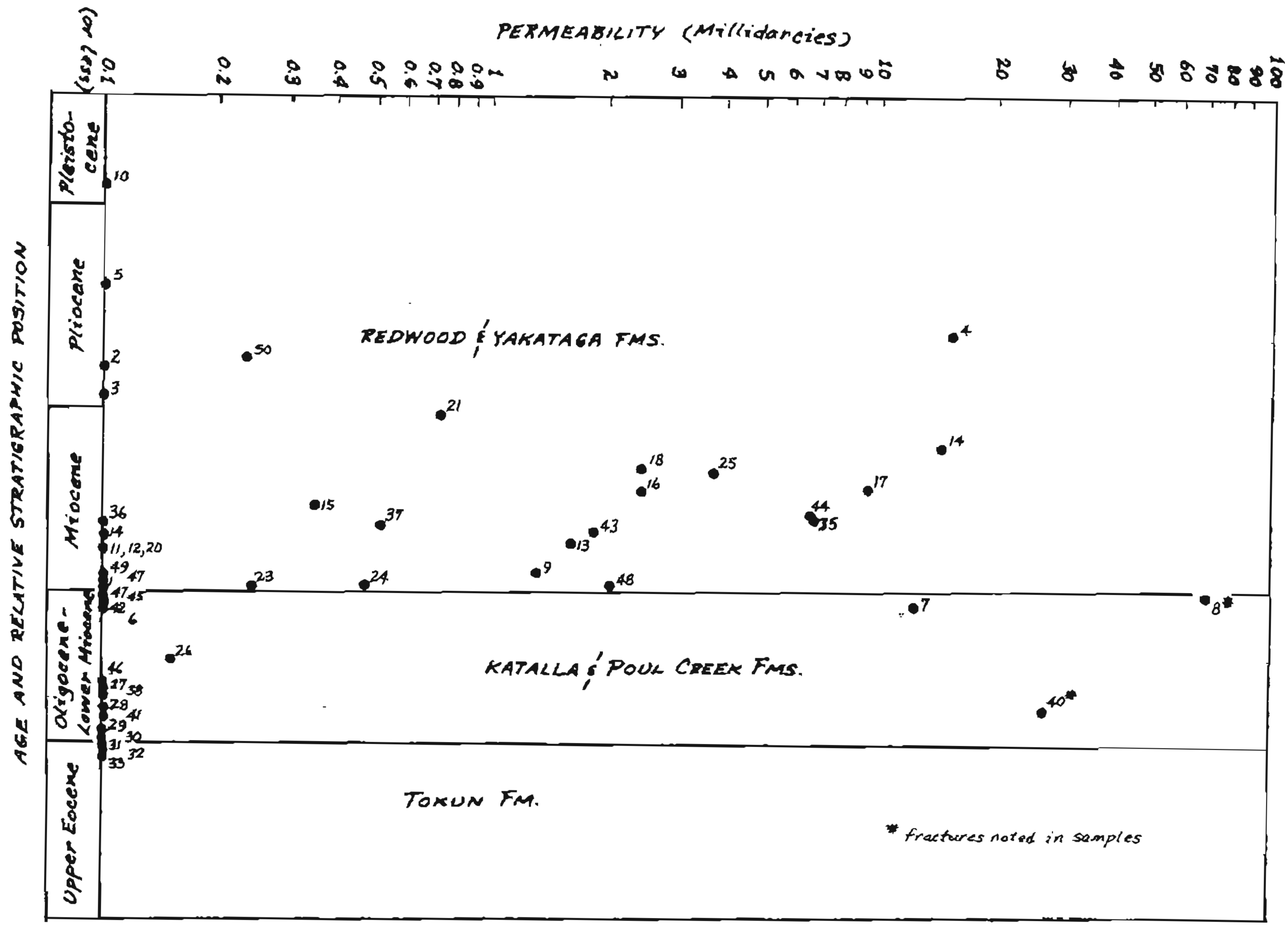


Figure 4. Permeability and relative stratigraphic position of analyzed sandstones, Gulf of Alaska Tertiary Province. (Numbers are the same as for figure 1; see Appendix 4 for data.)

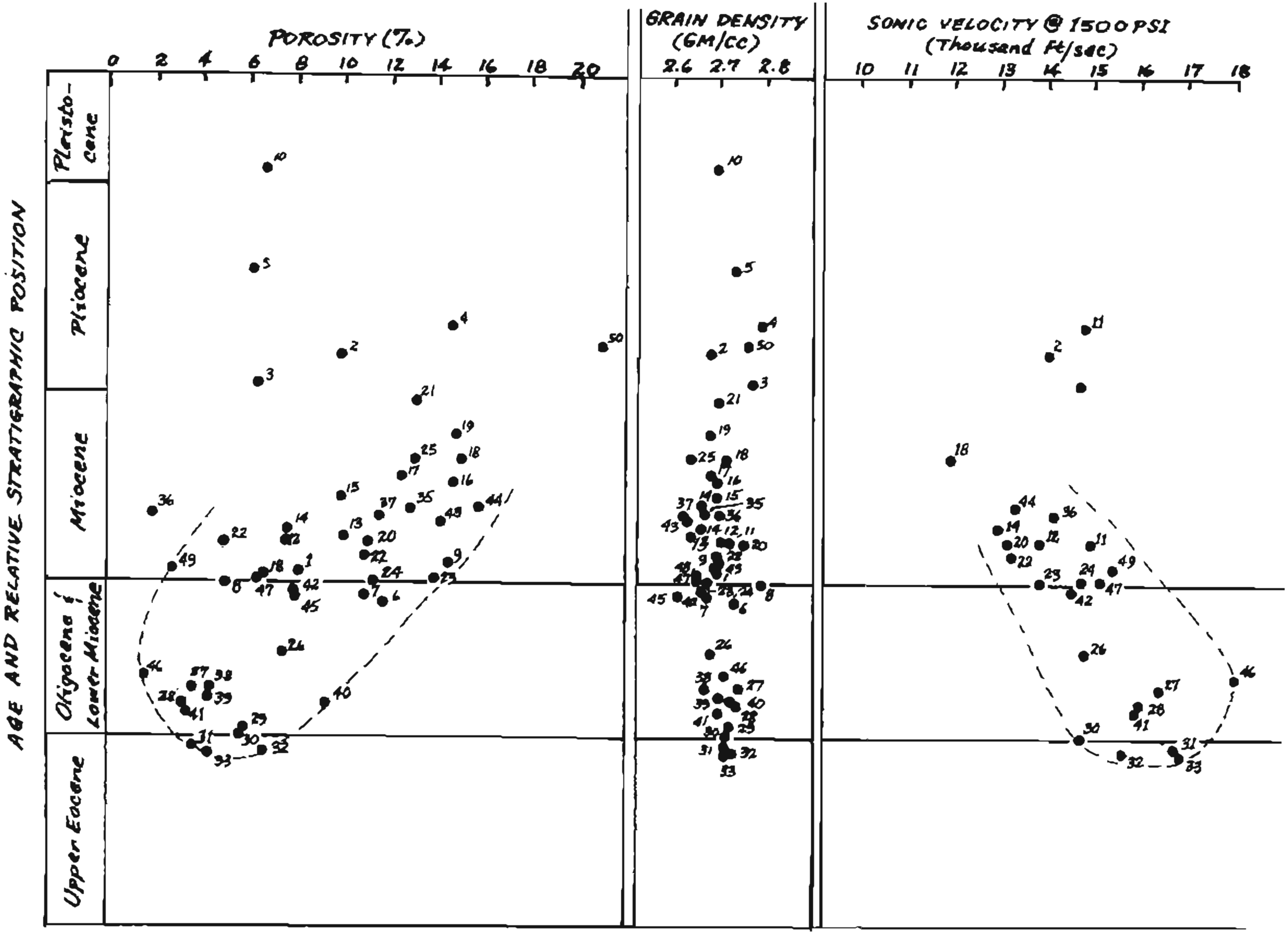


Figure 5. Porosity, grain density, and sonic velocity of analyzed sandstones, Gulf of Alaska Tertiary Province, as a function of relative stratigraphic position. (Numbers are the same as for figure 1; see Appendix 5 for data.)

Sandstones with permeability greater than 10 Md were found only in the upper part of the Poul Creek Formation and in the Yakataga Formation. In the two samples with values above 20 Md (fig. 4, #8=69 Md; #40=26 Md), interconnecting fractures were noted in thin sections. Within the Poul Creek and Yakataga Formations there appears to be no consistent relation of permeability to stratigraphic position or to geographic location.

Measured porosities (fig. 5) also are low, and range from 1.6 to 21.0 percent, with a mean of 8.8 percent. There is a general increase in porosity upward stratigraphically, suggesting that depth of burial is an important factor in controlling porosity. Sonic velocities (with a mean of 14,460 ft/sec @ 1500 PSI) generally decrease upward in the sequence. However, there is considerable scatter in the data, particularly in samples from the Yakataga Formation. Grain densities range from 2.61 to 2.79 gm/cc, averaging about 2.7, but show no consistent change with stratigraphic position.

Measurements of permabilities and porosities of 149 outcrop samples collected by Lyle and Palmer (1976) during detailed sampling of sandstone beds in the Yakataga Formation of the Yakataga district are quite variable but generally are greater than our values. Their permeability values that are greater than 100 Md, however, are restricted to sandstone beds in the middle and upper part of the Yakataga Formation, which may be more than 2000 metres above the prospective horizons near the contact between the Poul Creek and Yakataga Formations.

SANDSTONE / SHALE RATIOS

Sandstone/shale ratios of measured sections from which sandstones were obtained for this study (Table 1) vary widely. Ratios in the Yakataga Formation in areas as close together as Kayak Island (section #5, 1/0.9) and Suckling Hills (#7, 1/11.6) differ by a factor of more than ten. Generally differences are less, but even thick sandstone units tend to be lenticular within distances of a few kilometres or less. Most sandstone beds in these units appear to be channel fills; elongated shoreface sandstones are rare.

Quantitative information is limited on the sandstone/shale ratios of the lower Tertiary units at localities sampled for this study. The prevailing structural complexity of these rocks precludes measurement of thick sections. In the Prince William Sound area, flyschlike sedimentary rocks of the Orca Group may be as much as 50 percent sandstone, but individual beds are highly lenticular and generally are bounded by dense, hard argillite. In contrast, the equivalent shale of Haydon Peak in the Malaspina district probably has less than 10 percent sandstone in thick, laterally persistent beds. The Kulthieth Formation of the Yakataga and Malaspina districts has a high sandstone/shale ratio, as much as 1/0.7 at the Kulthieth River section west of Kulthieth Mountain (section #8) in the Yakataga district, and 1/0.6 in the Samovar Hills of the Malaspina district (section #13).

Table 1. Sandstone/shale ratios by measured section and stratigraphic unit

Measured section*		Formation	Thickness#		Sandstone/shale
1	MIDDLETON ISLAND	Yakataga	1203 m	(3950 ft)	1 / 10.1
3	MILLER HILLS	Redwood	1138	(3740)	1 / 7.5
4	WINGHAM ISLAND	Yakataga	211	(695)	1 / 3.1
		Katalla	371	(1220)	1 / 2.1
		Tokun	268	(880)	1 / 1.8
5	KAYAK ISLAND (W & N)	Yakataga	161	(530)	1 / 0.9
		Katalla	1005	(3300)	1 / 3.2
7	SUCKLING HILLS	Yakataga	1158	(3800)	1 / 11.6
		Katalla	201	(660)	1 / 7.2
	KULTHIETH RIVER	Poul Creek	1250 (estimated)	(4100)	1 / 100 ±
		Kulthieth	2467	(8040)	1 / 0.7
8	KULTHIETH MOUNTAIN	Yakataga	2423	(7950)	1 / 2.3
9	YAKATAGA REEF	Yakataga	262	(860)	1 / 2.0
		Poul Creek	204	(670)	1 / 2.6
13	SAMOVAR HILLS	Yakataga	1560	(5120)	1 / 2.6
		Kulthieth	828	(2700)	1 / 0.6
16	LA PEROUSE GLACIER	Yakataga	2042	(6700)	1 / 8.6

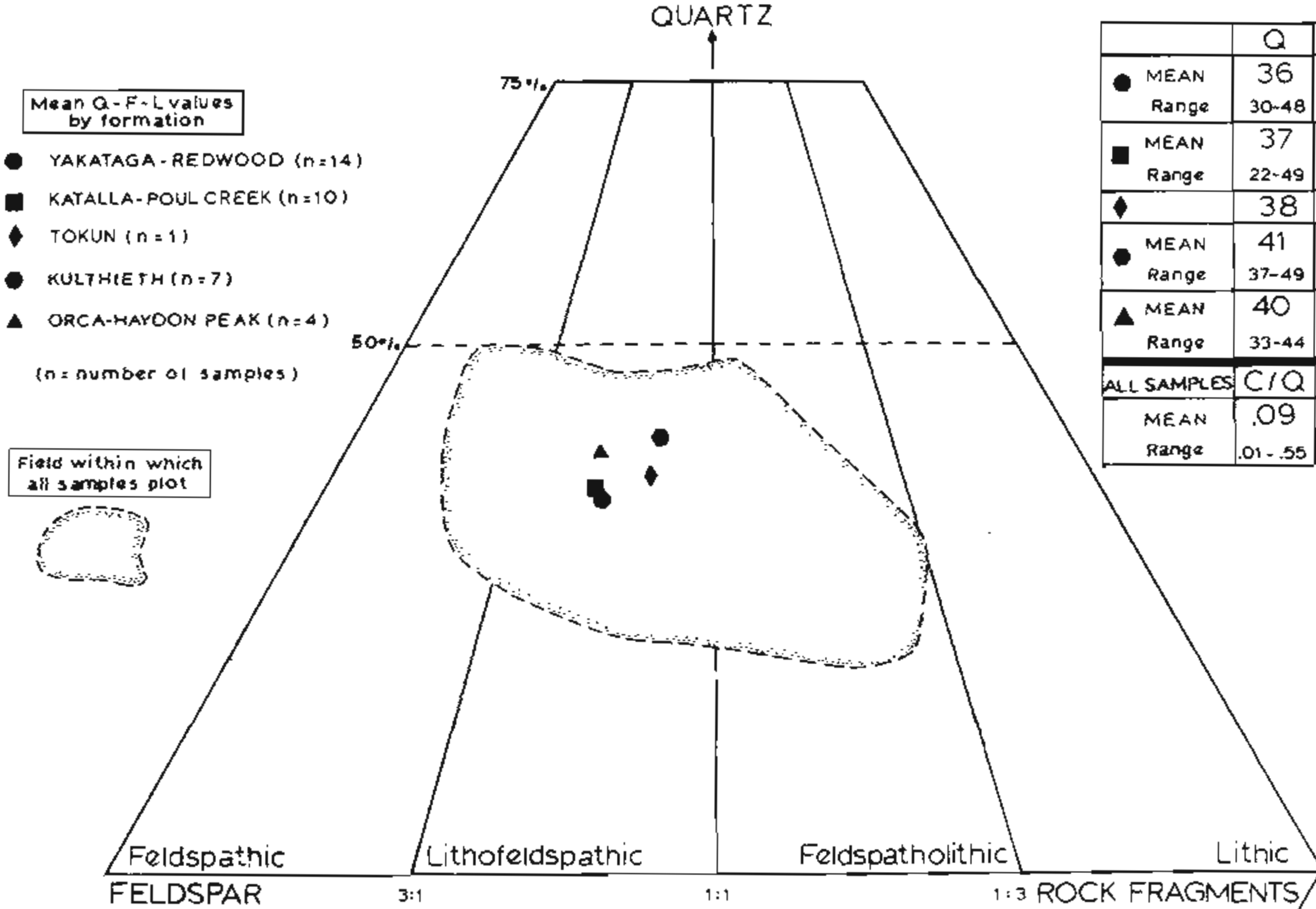
* Numbers correspond to those on figure 1

\# Does not include covered intervals

MINERALOGY

Sandstones of the GATP are subquartzose (i. e., total of quartzose grains is greater than 50 percent); although detrital modes vary widely, the average composition is lithofeldspathic (fig. 6). In general, with decreasing age of the samples, the percentage of quartzose grains (Q) decreases, the percentage of total feldspar grains (F) increases, and the percentage of rock fragments (L) remains about the same. Average modes for the entire suite of samples are as follows: polycrystalline quartz (C) constitutes about 10 percent of total quartz, subequal proportions of fresh and strongly altered altered plagioclase (P) constitute about 90 percent of total feldspar, and altered mafic to intermediate volcanic lithic grains (V) consitute about 70 percent of total lithic grains. There are no systematic changes in C, P, or V in samples of different ages. There is a systematic change, however, in proportions of the various lithic constituents. In the younger samples, the abundance of volcanic lithic grains decreases with decreasing age and weakly foliated metamorphic lithic grains (M) increase markedly. Sedimentary lithic grains (S) vary irregularly and appear to be largely of intraformational origin.

Q-F-L relations of the GATP sandstones are strikingly similar to those of Tertiary sandstones from the Queen Charlotte Basin (Galloway, 1974) and the western Olympic Peninsula and Vancouver Island (Stewart, 1974); they are very different from Q-F-L relations of Tertiary sandstones deposited in arc-related troughs, such as the Bristol Basin of



		Q	F	L	V	S	M
● (circle, 1st)	MEAN	36	41	23	64	7	29
	Range	30-48	24-53	12-33	48-83	3-22	7-47
■	MEAN	37	41	22	67	6	27
	Range	22-49	23-56	7-56	31-93	0-12	4-59
♦		38	36	26	81	3	16
● (circle, 2nd)	MEAN	41	34	25	74	11	15
	Range	37-49	23-48	10-41	54-90	0-28	0-46
▲	MEAN	40	39	21	92	3	5
	Range	33-44	17-52	8-50	86-96	0-4	0-11

ALL SAMPLES	C/Q	P/F	V/L
MEAN	.09	.92	.70
Range	.01-.55	.79-1.00	.31-.96

Q=total quartzose grains
C=polycrystalline quartzose grains
F=total feldspar
P=plagioclase
L=total rock fragments (RF)
V=volcanic RF
S=sedimentary RF
M=metamorphic RF

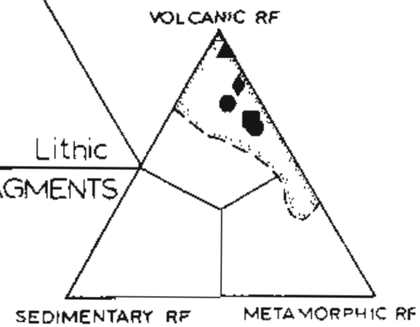


FIGURE 6 MINERALOGY OF 36 SANDSTONES, GULF OF ALASKA TERTIARY PROVINCE

Alaska and the Grays Harbor-Chehalis Basins of Washington (Galloway, 1974), which have many more lithic grains and plot much closer to the rock fragments apex of the Q-F-L diagram (fig. 6).

Percentage of heavy mineral assemblages and detrital biotite from GATP sandstones are listed in Table 2. Abundances of both total heavy minerals and biotite increase upward through the stratigraphic sequence. However, the same suites of heavy minerals, with slight shifts in proportions of constituents, occur throughout the sequence. Epidote, sphene, garnet, hornblende, and muscovite are present in nearly every sample. Other heavy mineral species, listed as "accessory" or "trace" in Table 2, occur less consistently, but also show no apparent stratigraphic control. Glauconite is the only exception. Although it is not present in the older Tertiary samples, glauconite abruptly appears in the middle Tertiary Katalla and Poul Creek Formations. It is particularly abundant in sandstones that are spatially associated with flows and plugs of alkali olivine basalt, which suggests that this glauconite formed in large part through alteration of basaltic detritus (Plafker, 1974). Glauconite of probable detrital origin also is present, but in much smaller amounts, in half of the samples from the younger Tertiary sequence.

Table 2. Percentages of heavy minerals and biotite by stratigraphic unit, Gulf of Alaska Tertiary Province

FORMATIONS#	HEAVY MINERALS*					BIOTITE		GLAUCONITE PRESENT
	PERCENT		ESSENTIAL	ACCESSORY	TRACE	PERCENT		% of total samples
	Mean	Range				Mean	Range	
Redwood-Yakataga (n=14)	5.0	0.2-9.8	EPIDOTE HORNBLENDE Garnet	Muscovite Sphene Zircon Chlorite Augite	Apatite Tourmaline Allanite Clinozoisite Staurolite Rutile	4.7	0.1-9.5	57
Katalla-Poul Creek (n=10)	2.2	0.2-4.2	GARNET Opaques Epidote	Muscovite Hornblende Zircon Augite Sphene Chlorite	Apatite Tourmaline Allanite Clinozoisite Staurolite	2.4	0.2-5.0	40
Tokun (n=1)	0.8		MUSCOVITE	Zircon Epidote		2.5		
Kultheith (n=7)	2.2	1.0-4.2	EPIDOTE Sphene Muscovite Garnet Zircon	Hornblende Augite	Clinozoisite Apatite Hypersthene	1.5	0.0-5.2	0
Orca-Haydon Peak (n=65)	1.8	0.2-6.4	EPIDOTE SPHENE HORNBLENDE Muscovite Garnet	Zircon Augite	Allanite Tourmaline Clinozoisite Chlorite Stilpnomelane Spinel	1.5	0.0 4.2	0

\# n = number of samples

* Listed within each category in order of abundance; capitalized minerals are dominant (ESSENTIAL = always present; ACCESSORY = usually present; TRACE = sometimes present)

PROVENANCE

Throughout the stratigraphic sequence, GATP sandstones appear to have been derived from similar, mixed sources. The moderate percentage of quartz and the presence, in all formations, of polycrystalline quartzose grains, foliated lithic grains, epidote, garnet, and abundant mica are characteristics of a "tectonic" provenance (Dickinson, 1970). The up-section increase of foliated lithic grains and biotite reflects either progressive "tectonization" of the source terrane or progressive erosion exposing deeper levels of an already tectonized terrane. In addition, high feldspar and low lithic percentages suggest a plutonic provenance; because little potash feldspar is present, the plutonic rocks were probably of intermediate composition. Recycling of detritus from a composite sedimentary and volcanic terrane is suggested by the abundant altered feldspar grains, the frequent occurrence of strongly altered mafic volcanic detritus, and the sporadic occurrence of quartz grains with overgrowths that have been slightly rounded.

These mineralogical characteristics indicate that the detritus apparently was derived from a tectonized and intruded sedimentary and volcanic terrane. For the older Tertiary sequences, the location of the terrane is problematical, but most likely was the adjacent Chugach terrane, which consists of low grade slate, graywacke, and greenstone west of the Copper River that is transitional into a high grade crystalline schist-gneiss-plutonic complex east of the Copper River. Certainly by Miocene time local sources are indicated. Conglomerate in the Redwood Formation and diamictites in the Yakataga Formation (Plafker and Addicott, 1976) have clasts consisting of biotite granodiorite, metabasalt, slate, graywacke, and layered gabbro. These clasts clearly are derived from the core of the nearby Chugach-Saint Elias-Fairweather Mountains. Multiple intra-formational unconformities in the younger Tertiary sequences and the recurrence of detrital glauconite in the younger rocks indicates that there was considerable reworking with possible second- (or third-) cycle sedimentation of locally-derived detritus.

DIAGENESIS

In general, sandstones of the GATP are texturally immature and mineralogically unstable. Porosity and permeability have been affected adversely by diagenetic alteration (Galloway, 1972). In our samples, alteration includes widespread framework modification, formation of phyllo-silicate coatings, and filling of interstices with authigenic cement or pseudomatrix. Galloway (1974) observed a sequential development of diagentic features with increasing depth of burial in sandstones from Tertiary basins in Washington, British Clumbia, and southwestern Alaska. Although it seems likely that a similar process may apply to GATP sand-stones, contemporaneous sedimentation and tectonism has complicated their interpretation. It is difficult, for example, to gauge the importance of compressive deformation or of tectonic thickening of sedimentary sequences in developing particular diagenetic features.

It is apparent, however, that the older Tertiary sedimentary sequences--

the Orca Group, the shale of Haydon Peak, and the Kulthieth Formation--generally have characteristic deep-burial diagenetic features similar to those of Stage 3 of Galloway (1974). Framework grains, particularly volcanic lithic grains and plagioclase feldspar, are moderately to strongly altered to chlorite, laumontite, and sericite. In a few cases, quart-prehnite-carbonate veins or even pumpellyite in volcanic lithic grains are present, particularly in the Orca Group. Interstices are filled with authigenic chlorite or with laumontite. Typically the chlorite forms irregular masses, but in a few cases it grows outward into former pore spaces (similar to "epimatrix" of Dickinson, 1970). Galloway (1974, fig. 7C) has found that these changes begin as shallow as 1500 m (5000 ft) in the Queen Charlotte Basin. In the GATP, deeper burial probably is indicated by partial recrystallization of some matrix minerals, advanced alteration of volcanic rock fragments, and a "welded" fabric produced by complex interpenetration of many grain boundaries.

The younger Tertiary sedimentary sequences typically have diagenetic features that are characteristic of shallower burial, such as carbonate cement and authigenic phyllosilicate coatings around framework grains (Stages 1 and 2 of Galloway). Carbonate cement apparently forms very early. It is especially typical of the Katalla-Poul Creek part of the younger Tertiary sequence, where it constitutes as much as 50 percent of some sandstones, but carbonate cement is present throughout the entire stratigraphic section. In sandstones with abundant carbonate cement, little other cement and only minor grain alteration and pseudomatrix are present--an indication that early formation of carbonate cement inhibits deterioration of the texture and mineralogy of framework grains.

Chemical alteration of labile constituents in the younger Tertiary units has resulted in the construction of phyllosilicate coatings upon susceptible grains. The most common coating is chlorite, but glauconite also is common. Remarkably, some samples from Tertiary units as young as Pliocene have laumontite or phyllosilicate pore-fillings and are tightly appressed. The significance of such local anomalies in diagenesis is not known, but framework alteration and pore-space reduction in the younger Tertiary rocks may have been heightened by proximity to loci of deformation.

Thus, direct comparison of age with depth of burial for GATP sandstones must be done cautiously. In general, however, a four-stage progression of diagenetic changes can be documented for GATP sandstones, and includes development of (1) carbonate cement (locally), (2) chlorite or glauconite coatings of framework grains, (3) interstitial chlorite or laumontite pseudomatrix or cement, and (4) prehnite, quartz, and carbonate in veins and patches.

SUMMARY OF TEXTURAL AND MINERALOGICAL CHARACTERISTICS BY STRATIGRAPHIC UNIT

The older Tertiary sequence exposed onshore is everywhere strongly indurated and multiply deformed. Deep burial of the Paleocene Orca Group and the probably coeval shale of Haydon Peak has reduced porosity to very low values. Framework grains have been moderately to strongly altered and subjected to sufficient pressure solution that grain boundaries generally are interpenetrative. Such interstices as remain are tightly plugged with pseudomatrix or laumontite cement. The upper Paleocene and Eocene Kulthieth Formation and the Eocene Tokun Formation are also strongly deformed and the sandstones are mineralogically unstable. Calculated packing densities for Kulthieth samples, in fact, are among the highest values of any sandstones that were studied; additionally, a laumontite or authigenic quartz cement which fills remaining pores is particularly characteristic of Kulthieth samples.

The exposed middle and upper Tertiary sequence onshore is less indurated and less strongly deformed than the lower Tertiary sequence. Sandstones in the Oligocene to lower Miocene Katalla and Poul Creek Formations have improved textural characteristics--better sorting, lower packing densities, and decreased matrix. Nonetheless, measured porosities and permeabilities are quite low, and grain densities and sonic velocities are high, perhaps because carbonate cement is prevalent. The continued presence of mineralogically unstable framework grains (particularly intraformational volcanic detritus) has resulted in considerable alteration of grains and pore space reduction by growth of phyllosilicate coatings and matrix. Sandstones from the Miocene and younger Redwood and Yakataga Formations are texturally more diverse than the older rocks. Although some sandstones are well sorted, poorly sorted tightly packed sandstones with interpenetrating grains are common. Unstable mineral grains are numerous and frequently have phyllosilicate coatings. In addition, primary matrix is more abundant and sandstone/shale ratios are much lower than in the Katalla and Poul Creek Formations. Thus, although there is a modest up-section improvement in sandstone reservoir characteristics throughout the Gulf of Alaska Tertiary Province, the occurrence of texturally mature sandstones with relatively little framework deterioration is very spotty. Failure of numerous onshore wells to hit economically productive reservoirs in favorable structural settings may be expectable because of the textural and mineralogical deterioration of the sandstones. Can improvement in sandstone reservoir properties be expected offshore? Until we know the relative importance of deformation and burial in GATP sandstone diagenesis, and until we are more certain of formation thicknesses and complexity of structural features offshore, extrapolations will be questionable.

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Appendix 1. Field descriptions of 74 analyzed samples by stratigraphic unit

Sample Number	Description
	REDWOOD FORMATION
1	Evenly bedded, slabby, hard, medium grained sandstone 8-10' thick in dark claystone
2	Conglomerate and sandstone interbedded in 300' thick sequence
	YAKATAGA FORMATION
3	Soft, friable, muddy and pebbly sandstone
4	Very fine grained calcareous sandstone 8' thick within conglomeratic sandy mudstone
5	Slabby, medium grained sandstone within conglomeratic muddy sandstone
9	Speckled, moderately sorted, angular, medium grained lithic sandstone 14' thick with channeling at base
10	Interbedded calcareous silty sandstone, pebbly sandstone, and hard sandy conglomerate
11	Hard, poorly sorted, tight, medium grained sandstone 10' thick with silty and pebbly laminae
12	Massive hard sandstone 10' thick, pebbly at base
13	Massive, medium grained sandstone 1' thick with pebbles at base and coal and plant fragments along bedding planes
14	Massive fine grained sandstone
15	Massive sandstone 30' thick with discontinuous pebbly layer 2" thick at base, grading into siltstone above
16	Well sorted, compositionally immature sandstone in thin beds within rhythmically interbedded flaggy siltstone, silty sandstone, and coaly partings
17	Slabby to flaggy, well sorted, medium grained sandstone 15' thick with silty partings and clayey matrix
18	Flaggy to massive, medium grained sandstone 8' thick within rhythmically alternating sandstone/siltstone couplets 1" thick

Appendix 1--continued

Sample number	Description
	<u>YAKATAGA FORMATION</u>--continued
19	Pebble conglomerate with sandy matrix and abundant clams 3.5' thick
20	Clean, finely laminated, fine grained sandstone in platey to flaggy beds, graded with siltstone in inch-scale couplets
21	Friable medium grained sandstone 80' thick with coarser pathces, pebbles, and a few thin siltstone laminae
25	Hard, mottled, medium grained arkosic sandstone with well rounded floating pebbles, interbedded with polymictic pebble-cobble conglomerate
35	Massive to slabby, poorly sorted, angular to subangular, biotite-rich sandstone in graded beds to 4' thick, interbedded with pebbly siltstone
36	Cross-laminated, hard, calcareous sandstone interbedded with conglomeratic sandy mudstone
37	Clean, planar laminated, fine grained sandstone 1-2' thick in friable sandy siltstone
43	Clean, medium grained arkosic sandstone at least 30' thick
44	Slabby, cross-laminated, medium to fine grained sandstone with channeling and bioturbation, interbedded with siltstone
45	Medium grained calcareous sandstone interbedded with conglomeratic mudstone
49	Massive or crudely stratified pebble-cobble conglomerate with 10% discontinuous sandstone and pebbly sandstone in beds to 2' thick
50	Hard, very fine grained, calcareous sandstone 4' thick in conglomeratic sandy mudstone
55	Pebble-cobble conglomerate with minor sandstone and mudstone in bed 31' thick
56	Massive to slabby, poorly sorted, angular to subangular, biotite-rich sandstone in beds to 4' thick
59	Angular, poorly sorted, fine to medium grained calcareous sandstone 4" thick with abundant dark lithic grains

Appendix 1--continued

Sample number	Description
	YAKATAGA FORMATION--continued
60	Hard, poorly sorted, cross-laminated, medium grained calcareous sandstone
71	Hard, very poorly sorted, fine grained sandstone
72	Hard, fine to medium grained calcareous sandstone 45' thick with 15-20' of conglomerate at base, local mud zones, and pebbles throughout
74	Friable, medium grained "salt-and-pepper" sandstone with scattered pebbles and coal
	KATALLA FORMATION
23	Slabby, clean quartzose sandstone 6-8' thick
24	Massive, angular to subangular, medium grained quartzose sandstone 15' thick
26	Slabby, clean, fine grained sandstone
27	Very fine grained calcareous sandstone interbedded with massive and bioturbated siltstone
28	Bioturbated, finely laminated, very fine grained calcareous sandstone 1' thick, rhythmically interbedded with sandy siltstone and siltstone
29	Thin- bedded, cross-laminated, very fine grained sandstone and silty sandstone in unit 64' thick
30	Finely laminated to platy, clean, calcareous sandstone 45' thick
34	Lenticular sandstone in rhythmically alternating slabby and massive beds as much as 18' thick, in part cross-laminated, calcareous, with plant remains on partings
38	Cross-laminated fine grained sandstone 10' thick interbedded with carbonaceous siltstone
39	Very lenticular, extensively bioturbated, slabby to flaggy, fissile, very fine grained calcareous sandstone 1.5' thick
40	Massive, cross-laminated platey sandstone with abundant carbonaceous material and minor siltstone partings

Appendix 1--continued

Sample Number	Description
41	KATALLA FORMATION -- continued
41	Mottled, friable, very fine grained calcareous sandstone 1' thick
42	Massive, clean, medium grained arkosic sandstone interbedded with foraminifera-rich siltstone and shale
46	Very bioturbated silty sandstone and siltstone
47	Massive, medium grained arkosic sandstone 8' thick interbedded with graded siltstone and silty sandstone
48	Very lenticular, crudely stratified, coarse grained sandstone 1' thick interbedded with granule conglomerate and pebble-cobble conglomerate with silty sandy matrix
54	Evenly laminated, very fine grained silty sandstone with lenticular calcareous beds
57	Flaggy to massive, uniformly bedded, medium to coarse grained sandstone with siltstone, in part calcareous, cross-laminated, and pebbly
58	Flaggy to slabby, fine to medium grained sandstone 6' thick with flute casts and organic shale interbeds
	POUL CREEK FORMATION
6	Massive, hard, fine to medium grained, moderately well sorted glauconitic sandstone
7	Interbedded glauconitic sandstone and siltstone
8	Hard glauconitic sandstone with a few resistant calcareous beds
61	Massive to flaggy, medium grained calcareous sandstone 26' thick with scattered pebbles and coal
73	Massive, very hard, pebbly glauconitic sandstone interbedded with zeolitized calcareous sandstone, all highly sheared
	TOKUN FORMATION
31	Uniformly layered, bioturbated, very fine grained sandstone 0.25-3' thick with plant chips and siltstone
32	Massive, cross-laminated sandstone 4' thick interbedded with siltstone
33	Planar- and cross-laminated sandstone 2.5' thick with siltstone above
34	Lenticular, rhythmically alternating slabby to massive sandstone, in part cross-laminated, galuconitic, calcareous, with plant remains
53	Slabby, cross-laminated sandstone interbedded with siltstone

Appendix 1--continued

Sample Number	Description
	KULTHIETH FORMATION
62	Slabby, hard, very clean, fine grained "salt-and-pepper" sandstone
63	Sandstone interbedded with dark, crumbly siltstone and silty sandstone
64	Massive, clean, biotite-rich, medium grained arkosic sandstone, mostly cross-laminated, interbedded with carbonaceous shale
65	Thick bedded, pebbly, plant- and log-bearing arkosic sandstone
68	Cross-laminated, medium to coarse grained sandstone, pebbly in part, 5-20' thick, with abundant wood and plant debris, interbedded with coal and carbonaceous siltstone
69	Coarse grained arkose and arkosic pebble conglomerate interbedded with siltstone with abundant wood
70	Highly sheared, very hard, pebbly glauconitic sandstone interbedded with zeolitic calcareous sandstone
	ORCA GROUP
51	Massive, quartz-veined, fine grained sandstone, tightly folded with steep axial planes
52	Slabby to massive, very hard, baked wacke sandstone 8' thick with veining throughout, interbedded with dark phyllite and mafic volcanic rocks
	SHALE OF HAYDON PEAK
66	Thick, calcareous, fine grained sandstone with shale chips, interbedded with dark siltstone
67	Very hard, pebble-cobble conglomerate with sandy matrix and slightly elongated clasts, interbedded with sandstone and siltstone

Appendix 2. Sandstone fabric analysis by stratigraphic units (sample numbers the same as for figure 1)

Sample Number	Framework Sorting	Framework Alteration[1]	Packing Density (estimated)	Packing Density (calculated)	Principal Cementing Agent[2]	Type of Grain Contacts[3]	Percent Matrix
				REDWOOD FORMATION			
1	Moderate	--	Very high	99	A	L, C, S	<5
2	Poor	F, L to clay	High	86	A	L, C, minor S	--
				YAKATAGA FORMATION			
3	Poor	F, L to clay	Low	80	B>> A	F, P, L	>15
4	Mod. well	--	Mod. high	92	A = B	P, L, C	<5
5	Poor	--	Moderate	82	Primary matrix	F, P, L	15
9	Moderate	L, F margins to zeolite, chlorite, & sericite	Mod. high	92	A, minor B	Mostly C	21
10	Moderate	F to clay, CO_3	Mod. high	79	B > A	L, C, minor F	--
11	Moderate	Some Q, F overgrowths	Mod. high	88	A, minor B	L, C, minor F	16
12	Poor	F to chlorite	Very high	92	A>> B	L, C	--
13	Mod. well	F to clay	Very high	99	A	L, C, minor S	--
14	Mod. well	F to clay	Very high	98	A > B	L, C, minor S	~10

[1] Q = quartz; F = feldspar; L = rock fragments; CO_3 = carbonate; M = matrix

[2] A = grain contacts; B = authigenic cement

[3] S = sutured; C = concavo-convex; L = long; P = point (tangential); F = floating

Appendix 2--continued

Sample Number	Framework Sorting	Framework Alteration[1]	Packing Density (estimated)	Packing Density (calculated)	Principal Cementing Agent[2]	Type of Grain Contacts[3]	Percent Matrix
			YAKATAGA FORMATION--continued				
15	Moderate	L to chlorite F to glauconite	Moderate	75	A = B	P, L, C	15
16	Well	Q, F to glauconite	High	62	A>> B	L, C, minor P	15
17	Mod. well	--	Very high	99	A	L, C, minor S	--
18	Moderate	--	--	--	--	--	--
19	Mod. well	Q, F, L to glauconite	High	88	A > B	L, C	17
20	Moderate	F, L to clay	Very high	98	A>> B	L, C	--
21	Mod. well	F, L to clay	Very high	99	A	L, C	--
22	Mod. well	L to clay	Very high	78	A > B	L, C	--
25	Moderate	--	Very high	98	A, rare B	L, C, minor S	--
35	Moderate	F, L to CO_3	High	83	B = A	F, L, C	--
36	Moderate	L, F to CO_3	Low	54	B	F, L, minor C	--
37	Mod. well	F, L to CO_3	Moderate	92	A, minor B	L, C, F, very minor S	--
43	Poor	Q with overgrowths	High	88	A>> B	L, C micro S	14
44	Mod. well	--	Very high	98	A>> B	L, minor C	--
45	Poor	--	Low	57	Primary matrix	F	--
49	Moderate	L to CO_3	Moderate	72	B > A	F, L, C	--
50	Well	F to chlorite	Mod. low	84	B > A	F, L, minor S	--
55	Well	Q, F, L to CO_3	High	88	A	C, L	14

Appendix 2--continued

Sample Number	Framework Sorting	Framework Alteration[1]	Packing Density (estimated)	Packing Density (calculated)	Principal Cementing Agent[2]	Type of Grain Contacts[3]	Percent Matrix
			YAKATAGA FORMATION--continued				
56	Moderate	Q, F, L to CO_3	Mod. high	ca. 90	A>> B	C, L	12
59	Mod. well	Q to CO_3	Low	--	B>> A	F, local P, L	1
60	Well	Q, Mx to CO_3	Low	--	B>> A	F, local P, L	2
71	Poor-very poor	L to chlorite	High	80	A > B	L, C, micro S, F in matrix	24
72	Poor	L to CO_3, chlorite, Q to glauconite	Moderate to Low	81	A = B	F in matrix, P, L	4
			POUL CREEK FORMATION				
6	Mod. well	Q, F, L to glauconite & siderite ?	Moderate	89	A = B	L, P, C	14
7	Moderate	??	Moderate	--	A > B	L, P, C	--
8	Well	F to chlorite	High	89	A>> B	L, C	--
61	Mod. well	--	Moderate to Low	81	A > B	P, L, C	14
73	Well	Q, F to sericite & chlorite	Mod. high	80	A > B	F in matrix, P, C	24
			KATALLA FORMATION				
23	Mod. well	--	Mod. high	92	A>> B	C, L	5

Appendix 2--continued

Sample Number	Framework Sorting	Framework Alteration[1]	Packing Density (estimated)	Packing Density (calculated)	Principal Cementing Agent[2]	Type of Grain Contacts[3]	Percent Matrix
KATALLA FORMATION--continued							
24	Mod. well	L to clay	Mod. high	91	A>> B	C, L	5
26	Mod. well	F to CO_3, clay	Mod. high	93	A>> B	L, C	--
27	--	--	--	--	B	F	--
28	Moderate	F, L to CO_3	Moderate	81	B>> A	L, F, minor C	--
29	Well	Q, F, to CO_3, chlorite & sericite	Low	77	B>> A	F (C, L in patches)	5
30	Well	Q, F, L to Chlorite, sericite, & CO_3	Low	78	B>> A	F (C, L in patches)	6
38	Moderate	F, L to CO_3	Moderate to Low	63	B > A	C, L, F, minor S	--
39	Mod. well	F, L to CO_3	Low	61	B>> A	F, L, C	--
40	Mod. well	L to CO_3	Moderate	93	A>> B	F, L, C	--
41	Moderate	Mx to CO_3	Very low	43	B>> A	F, minor P, L	--
42	Poor	F, L to CO_3	High	91	A>> B	C, L, incipient S	14
47	Mod. well	L to zeolite & chlorite, F to sericite	Very high	90	A>> B	L, C, micro S	15
48	Mod. well	F to sericite & zeolite, clay to chlorite	High	88	A>> B	C, micro S	12
54	Well	Q, F, L to chlorite & CO_3	Low	--	B>> A	F, local P, L, C	2

Appendix 2--continued

Sample Number	Framework Sorting	Framework Alteration[1]	Packing Density (estimated)	Packing Density (calculated)	Principal Cementing Agent[2]	Type of Grain Contacts[3]	Percent Matrix
			KATALLA FORMATION--continued				
57	Poor	Q to CO_3	Low	--	B > A	P, F	2
58	Well	Q, F, L to CO_3, sericite & chlorite	High	82	A > B	L, C, micro S	18
			TOKUN FORMATION				
31 32 33 53	Moderate	Q, F, L to CO_3	Low	--	B>> A	F	8
			KULTHIETH FORMATION				
62	Well	F to zeolite	High	91	A, minor B	L, C, micro S	18
63	Mod. well	F to sericite	High	92	A, minor B	L, C	14
64	Mod. well	F, L, to sericite & chlorite, Q overgrowths	Very high	98	A, very minor B	L, C, micro S	25
65	Moderate	F to CO_3 and prehnite	High	98	A	L, C, minor S	8
68	Mod. poor	F to zeolite & prehnite	Very high	76	A, minor B	L, C, S	16
69	Mod. well	Q, L to CO_3 & zeolite	Very high	94	A, very minor B	L, C, micro S	11

Appendix 2--continued

Sample Number	Framework Sorting	Framework Alteration[1]	Packing Density (estimated)	Packing Density (calculated)	Principal Cementing Agent[2]	Type of Grain Contacts[3]	Percent Matrix
			SHALE OF HAYDON PEAK				
66	Mod. well	Q, F, L to chlorite & CO_3	Mod. high	--	A, minor B	P, L, C	24
67	Poor	L to zeolite & prehnite, Q overgrowths	High	81	A, minor B	L, C, minor S	11
			ORCA GROUP				
51	Poor	Q, F, L to zeolite	Low	80	B>> A	F, minor P	34
52	Poor	Q, F, L to chlorite, framework sheared & silicified	Very high	--	A	C, S	18

Appendix 3. Binocular examination of 32 slab samples

Sample Number	Grain Interpenetration Observed?	Rate of Water Absorption	Reaction to Dilute HCl	Possibility of Fracture Porosity	Induration-Friability
YAKATAGA FORMATION					
9	No	Slow	Slight	Nil	--
11	Possibly	Slow	No	Nil	Not friable
15	No	Rapid	No	Nil	Not friable
16	No	Moderate	No	Nil	Not friable
19	No	Moderate	No	Nil	Not friable
42	Possibly	Moderate to slow	Slight	Nil	Weakly friable
55	??	Very slow	Slight	Yes	--
56	Yes	None	Slight	Nil	Weakly friable to beds
59	No	None	Strong	Possibly, but CO_3 filled	Not friable
60	Yes	Very slow	Strong	Nil	Not friable
71	No	None	No	Nil	Highly indurated
72	No	Moderate	Strong	Yes	Weakly friable
POUL CREEK FORMATION					
6	No	Moderate to slow	No	Nil	Slightly friable
61	No	None	No	Yes	Not friable
73	Yes	None	No	Nil	Not friable
KATALLA FORMATION					
29	Possibly	Slow	Strong	Nil	Not friable
30	??	Very slow	Strong	Nil	Not friable
47	Yes	Very slow	No	Nil	Slightly friable

Appendix 3--continued

Sample Number	Grain Interpenetration Observed	Rate of Water Absorption	Reaction to Dilute HCl	Possibility of Fracture Porosity	Induration-Friability
KATALLA FORMATION--continued					
48	Yes	None	No	Nil	Not friable
54	No	Rapid	Strong	Yes	Slightly friable
57	No	None	Yes	Nil	Not friable
58	??	None	No	Yes	Not friable
TOKUN FORMATION					
53	No	Slow	Moderate	Nil	Not friable
KULTHIETH FORMATION					
62	No	Moderate to rapid	No	Yes	--
63	Yes	None	No	Possibly, but CO_3 filled	Not friable
64	Yes	Very slow	No	Nil	Slightly friable
65	Yes	None	No	Nil	Well indurated
68	Yes	Very rapid	No	Slight	Moderately friable
69	Yes	Very slow	No	Nil	Not friable
SHALE OF HAYDON PEAK					
66	??	Slow	Moderate	Yes	Not friable
67	Yes	None	Slight	Nil	Not friable
ORCA GROUP					
52	Yes	None	Slight	Nil	Highly indurated

Appendix 4. Permeability, porosity, and grain density data for 50 sandstones, Gulf of Alaska Tertiary Province. (Analyses by Core Laboratories, Inc., Dallas, Texas)

Sample Number	Air Permeability, Md.	Porosity, Percent	Grain Density, gm/cc
	YAKATAGA REEF		
6	0.07	11.7	2.73
7	12	10.9	2.67
8	69	5.0	2.79
9	1.3	14.4	2.70
	KULTHIETH MOUNTAIN		
11	0.02	4.9	2.72
12	0.05	7.5	2.70
20	0.07	11.1	2.72
13	1.6	10.0	2.64
14	0.06	7.6	2.66
15	0.35	9.9	2.69
16	2.4	14.7	2.69
17	9.2	12.5	2.68
18	2.4	15.0	2.71
19	14	14.8	2.68
21	0.73	13.1	2.69
5	0.02	6.1	2.73
	MILLER HILLS		
1	0.04	8.1	2.69
2	0.03	9.9	2.68
	LA PEROUSE GLACIER		
3	0.10	6.4	2.77
50	0.23	21.0	2.76
4	15	14.6	2.79
	MIDDLETON ISLAND		
10	0.07	6.7	2.69
	KAYAK ISLAND		
24	0.47	11.2	2.67
23	0.24	13.9	2.67
25	3.7	13.0	2.64
26	0.15	7.4	2.68
27	0.01	3.6	2.74
28	0.01	3.2	2.74
29	0.04	5.8	2.72
30	0.02	5.6	2.71

Appendix 4--continued

Sample Number	Air Permeability, Md.	Porosity, Percent	Grain Density, gm/cc
KAYAK ISLAND--continued			
42	0.07	7.9	2.66
43	1.8	14.1	2.63
44	6.5	15.8	2.66
45	0.01	7.9	2.61
46	0.01	1.6	2.71
47	0.05	6.4	2.65
48	2.0	6.5	2.65
49	0.02	2.8	2.69
22	0.05	10.9	2.69
WINGHAM ISLAND			
31	0.01	3.6	2.71
32	0.01	6.6	2.73
33	0.01	4.2	2.71
34	10	6.3	2.67
35	6.7	12.9	2.66
36	0.01	1.9	2.70
37	0.51	11.5	2.62
38	0.08	4.3	2.67
39	-- (fractured)	4.3	2.70
40	26	9.2	2.72
41	0.01	3.4	2.70

Appendix 5. Porosity and sonic velocity data for 25 sandstones, Gulf of Alaska Tertiary Province. (Analyses by Core Laboratories, Inc., Dallas, Texas)

Sample Number	Porosity, Percent	Transit time, Micro-seconds/ft, at Effective overburden pressures, PSI, of					
		300	600	1000	1500	2000	4000
		KULTHIETH MOUNTAIN					
11	4.9	69.0	68.0	67.6	67.0	66.9	64.9
12	7.5	75.8	74.9	73.9	72.4	71.4	68.9
20	11.1	85.0	82.4	79.8	76.6	77.4	83.8
14	7.6	86.3	84.8	80.4	77.4	75.6	67.3
18	15.0	97.2	92.0	87.4	83.8	81.1	73.9
		MILLER HILLS					
2	9.9	79.3	77.8	75.5	71.6	70.8	66.2
		LA PEROUSE GLACIER					
3	6.4	76.5	72.8	70.5	68.1	67.1	64.1
4	14.6	69.8	69.0	68.1	67.5	66.3	64.9
		WINGHAM ISLAND					
31	3.6	60.3	60.0	60.0	59.8	59.3	58.8
32	6.6	65.3	65.0	64.2	63.9	63.6	62.5
33	4.2	69.1	62.4	61.0	59.4	58.9	58.3
36	1.9	71.5	71.5	71.1	70.7	70.3	69.5
41	3.4	65.2	64.4	63.5	62.7	61.8	61.4
		KAYAK ISLAND					
24	11.2	76.5	72.8	70.5	68.1	67.1	64.1
23	13.9	80.5	77.4	75.0	72.6	71.4	68.4
26	7.4	69.8	69.0	68.1	67.5	66.3	64.9
27	3.6	62.3	61.7	61.7	61.1	60.5	59.8
28	3.2	63.3	63.3	62.9	62.6	62.6	61.1
30	5.6	71.8	70.5	69.2	67.9	66.7	65.4
42	7.9	78.9	74.4	71.6	68.9	66.6	63.8
44	15.8	83.9	81.3	77.9	75.3	73.9	70.3
46	1.6	56.2	55.9	55.7	55.5	55.5	55.0
47	6.4	74.1	70.0	68.1	66.3	64.4	63.8
49	2.8	67.2	66.6	65.5	65.0	63.3	61.6
22	10.9	78.5	77.8	77.1	76.0	75.1	74.1