HEAVY MINERAL ANALYSIS OF SEDIMENTARY ROCKS OF NORTHERN ALASKA

by

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ABSTRACT

The Navy Oil Unit of the United States Geological Survey has been investigating the geology of Naval Petroleum Reserve No. 4, northern Alaska. As part of this program, heavy-mineral samples were prepared from cores of the test wells and core holes and studied to determine stratigraphic correlations. Using the following criteria: (1) presence of diagnostic minerals or mineral suites; (2) relative abundance of specific minerals; (3) degree of rounding of mineral grains; (4) distinctions as to grain form; eight heavy-mineral zones have been recognized in Triassic, Jurassic, Cretaceous, and Quarternary sedimentary rocks. Correlations based on these zones are shown. Source areas and rocks are discussed in relation to geologic history and genesis of the Mesozoic and Quarternary sedimentary rocks.

INTRODUCTION

Naval Petroleum Reserve No. 4, Alaska, is an area of 37,000 square miles, the boundaries of which are shown in plate 1. In 1923, under the Harding Administration the Reserve was withdrawn from public entrance. In 1944, the Office of Naval Petroleum Reserves, U. S. Navy, began investigations of petroleum potentialities. The Navy Oil Unit of the U. S. Geological Survey was assigned the task of studying the geology of the area. Subcontracts were let for the geophysical work and drilling.

During the past few years numerous core tests and test wells have been drilled in Naval Petroleum Reserve No. 4. This paper presents the results of a study to correlate, by use of heavy minerals, stratigraphic horizons in some of the core tests and test wells in the Barrow, Cape Simpson, Umiat, Fish Creek, Topagoruk, Meade, and Oumalik Rivers areas. In addition these correlations may help to clarify stratigraphic relationships and the geologic history of Naval Petroleum Reserve No. 4 as a whole.

ACKNOWLEDGMENTS

Prior to 1949 qualitative heavy-mineral studies had been done by Ernest H. Lathram of the Navy Oil Unit. Through his cooperation, and with the permission of Ralph L. Miller, Chief of the Navy Oil Unit, United States Geological Survey, sample material was made available for a detailed quantitative study to be used as a Master's thesis. Unpublished geologic reports, well logs, geophysical data, paleontologic data, and all pertinent information were made available to the author. Grateful appreciation is extended to Miss W. H. Eckstein, United States Geological Survey, for editing the manuscript.

PHYSIOGRAPHY AND GENERAL GEOLOGIC HISTORY

Physiography.—Northern Alaska may be divided into three physiographic provinces from north to south: the Arctic Coastal Plain province, the Arctic Foothills province, and the Brooks Range province. (See Pl. 1.)

The Arctic Coastal Plain is a flat tundra area with thousands of shallow lakes. Along its southern border are a few hills, none of which exceed 1,000 feet in altitude. The annual rainfall is 5-7 inches. Many streams drain the region but all are sluggish and meandering, with braided channels. Most of the stream water is derived from the melting of winter snows.

In the Arctic Foothills province the linear arrangement of hills is controlled by the structures in the underlying folded and faulted Mesozoic sedimentary rocks. These structures in general strike east. The Colville River with its tributaries is the major drainage system. It flows east through most of the Arctic Foothills before it turns north to empty into the Arctic Ocean. The main channel of the Colville River is braided, as are some of the tributaries, but many of the smaller streams have steep gradients. In the northern section of the province the maximum altitude of hills and ridges is 2,000 feet; in the southern section the maximum is more than 3,000 feet.

The maximum altitude in the Brooks Range province is over 8,000 feet. The crest of the east-trending Brooks Range is the divide between drainage to the Arctic Ocean and the south-flowing waters of the Yukon Valley.

Major folds and large thrust faults with resultant displacements to the north produce a complex structure within the mountains. The contact of the overthrust Paleozoic rocks of the Brooks Range with Mesozoic rocks in the foothills coincides with the northern boundary of the Brooks Range province. The strike of major structures is east.

Geologic history.—During the Paleozoic era the area embraced by the Brooks Range province, Arctic Foothills province, and the southern part of the Arctic Coastal Plain province was occupied by a major east-trending geosyncline. At its eastern end, its axis swung south to join the Cordilleran geosyncline. This geosyncline received sediments primarily from a northerly source throughout the Paleozoic. A thick section of Devonian and Carboniferous sedimentary rocks constitutes the major part of the Brooks Range.

During the early Mesozoic era sediments accumulated in considerable thickness in the Arctic Foothills region but in lesser thickness near Point Barrow. During this time complex folds and thrust faults were formed, igneous masses emplaced, and uplift occurred in the Brooks Range as late as Early Cretaceous. This uplifted area became the source for younger Cretaceous and Tertiary sediments that were deposited north of the mountains. These younger rocks consist of nonmarine formations that grade northward into marine facies in the Coastal Plain region.

A Tertiary orogeny further deformed the Brooks Range. Peneplanation, Quaternary uplift, and erosion by streams and glaciers followed. The Brooks Range was the site of alpine glaciers during the Pleistocene, whereas the northern part of the Arctic Foothills and the Arctic Coastal Plain provinces were not covered by glaciers. The mantle of unconsolidated gravel that covers most of the coastal plain in part may represent glacial debris.

An igneous body of dioritic composition about 30 miles long is exposed at 157° W. long., 68° N. lat., another of granitic composition occurs at 144° W. long., 69°20' N. lat. A third intrusive mass, also of granitic composition and possibly of batholytic dimensions is exposed in the Laird Mountains. Mafic sills and dikes are intruded along major faults and fractures throughout the Brooks Range. The Laird Mountain granite, the diorite, and the mafic sills and dikes are of Mesozoic age.

STRATIGRAPHY

A basement complex of pre-Devonian phyllite and argillite underlies Naval Petroleum Reserve No. 4. In the Barrow area, as shown in drill cores, rocks of Triassic age overlie the basement complex; south in Topagoruk Test Well No. 1 late Paleozoic rocks lie above the basement complex. In test wells at Barrow, Cape Simpson, and Topagoruk, the Kingak shale of Jurassic age has been identified immediately above the Triassic. This unit is entirely marine, and consists of black shale, silty layers, and calcareous ironstone lenses.

Unconformably above the Jurassic rocks are Cretaceous intertonguing marine and nonmarine sandstone and shale. The sandstones are moderately to well-indurated low-rank graywackes; the grains are angular, and range from very fine to very coarse. The Cretaceous system has a maximum known thickness of about 13,000 feet 60 miles south of Fish Creek Test Well No. 1. At Point Barrow the system is about 2,000 feet thick.

Resting on the eroded surface of the Cretaceous rocks is the Gubik formation of Pleistocene age. The Gubik formation ranges in thickness from very thin to a maximum of 125 feet and consists of gravel and sand. The grains are predominantly well rounded. The top of this formation is the present land surface. Paleontologic investigations have been extensive and ages of the units in Naval Petroleum Reserve No. 4 are well established. Table 1, page 7, shows the stratigraphic nomenclature.

HEAVY-MINERAL STUDIES

Sample preparation

Because the majority of sedimentary rocks in Naval Petroleum Reserve No. 4 from which the heavy-mineral samples are obtained are graywackes, the sampling technique is an important factor in determing results. The graywackes represent poorly sorted sediments; therefore a spot sample would include only those minerals deposited under the particular hydraulic conditions represented by the thickness of the sample. A composite of several spot samples, however, would include a larger variety of minerals deposited under varying hydraulic conditions. A similar net result is attained if a length of drill core is disaggregated and a heavy-mineral fraction separated from it. Heavy mineral core samples from the test wells and core test were therefore prepared in the following manner. A 10-foot section of sandstone was cored; from this about 6 feet of core was the average recovery. Several small sections of this 6-foot core were taken, in effect a composite of the cored interval. The composite sample was then disaggregated as shown in the flow sheet on page 8.

An adequate heavy-mineral fraction could be obtained from these composite samples. The fraction was quartered and mounted in a suitable slide with Canada balsam (N=1.54) or aroclor (N=1.66).

Period	Epoch	Group	Formation			
Quaternary	Pleistocene		Gubik			
Tertiary			Sagavanirktok			
Cretaceous	Upper	Colville	Nonmarine		Marine	
Cretaceous	Upper	Colville	Prince Creek fm.	Kogosukruk tongue	Schrader Bluff formation	Sentinel Hill member
Cretaceous	Upper	Colville	Prince Creek fm.	Tuluvak tongue	Schrader Bluff formation	Tuluga member
Cretaceous	Upper	Colville	Prince Creek fm.	Tuluvak tongue	Schrader Bluff formation	Seabee member
Cretaceous	? Lower	Nanushuk	Chandler fm.	Niakogon tongue	Umiat formation	Topagoruk member
Cretaceous	Lower	Nanushuk	Chandler fm.	Hatbox tongue	Umiat formation	Tuktu member
Cretaceous	Lower	Killik	Torok formation			
Cretaceous	Lower	Killik	Okpikruak formation			
Jurassic		Killik	Kingak formation			
Triassic			Shublik formation			
Permian			Sadlerochit formation			

Table 1. Stratigraphic names of post-Carboniferous rocks

FLOW SHEET FOR HEAVY-MINERAL DISAGGREGATION OF SANDSTONE

UNITED STATES GEOLOGICAL SURVEY FAIRBANKS LABORATORY

1. Approximately 120 grams of crushed sandstone.

2. Split in Riffler to approximately 60 grams.

3a. Test first for carbonate with HCl. If bubbles appear, treat with about 150 ml. of dil. (0.1N HCl) and heat to break down the calcareous material. Time of treatment will depend upon amount of calcareous material. If noncalcareous proceed directly to step 5.

3b. Put unused portion back in bag and label.

4. Wash off acid by decanting in water. Dry thoroughly.

5. If necessary use 40-mesh and/or 60-mesh A. S. T. screens. Hand shake in 80-mesh and 200-mesh. Check all screens under binocular to determine degree of disaggregation. If aggregates remain, work down to grain size with mortar and pestle.

6. Shake in sieve shaker for about 10 minutes.

7a. Combine the -80-mesh and +200-mesh fraction in a labeled beaker.

7b. Discard fraction in the pan.

8. Test for calcareous content. If any, repeat treatment with HCl acid as in step 3a.

9. Repeat thorough washing and dry in beaker or filter paper.

Ready for bromoform separation.

FLOW SHEET (CONT'D)

1. Pour sand slowly into separatory funnel which is approximately three fourths full of bromoform of 2.7 sp. gr. Stir floating sand gently several times to insure a complete separation. Use a different stirring rod for each sample to avoid contamination.

2a. Release the +2.7 material into a labeled filter paper. This is the medium and heavy fraction. Return bromoform to stock bottle.

2b. Repeat steps 2a and 3a to clear the light fraction from the funnel.

3a. Wash filter paper and concentrate thoroughly with alcohol and dry.

3b. Bottle and label the light fraction. Split in microsplit if necessary.

4. Repeat steps 1, 2, and 3 using methylene iodide with 3.0 sp. gr.

5a. Bottle and label 3.0 (heavy) fraction.

5b. Bottle and label +2.7 -3.0 (medium) fraction.

Samples were obtained from the following wells and core tests: South Barrow Test Wells Nos. 1, 2, and 3; Simpson Test Well No. 1; Simpson Core Tests Nos. 1-4, 6-20, 13-17, 23-26, and 28; Umiat Test Wells Nos. 1 and 2; Fish Creek Test Well No. 1; Topagoruk Test Well No. 1; Oumalik Test Well No. 1; Meade Test Well No. 1.

Examination of samples

The slides from which the following data were computed were examined under a petrographic microscope. Traverses of each slide were made until a sufficient number of grains had been counted. Traverses were made by starting in the corner of the slide, progressing across the slide in a straight line and counting each of the grains that passed through the field of view. Each traverse was spaced so that one field border was tangent to the border of the previous traverse. In some of the slides the grains were so few in number that the entire slide was covered, in others, this method resulted in covering at least half of the slide.

The combination of lenses best suited for this procedure was found to be one in which the magnification was 200 diameters, using an 8mm. 20x objective and a 10x eye piece. When it became necessary to observe interference figures, a 4mm., 45x objective with a numerical aperture of 0.35 was used.

Grain counts

For each sample the nonopaque heavy-mineral grains were counted. Krumbein and Pettijohn 1/ show that a count of 400 grains per sample is

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1/ Krumbein, W. C. and Pettijohn, F. J., Manual of sedimentary petrology, pp. 470-472, Appleton-Century-Crofts, 1938.

suitable for heavy-mineral analysis. Counts of this magnitude will have a small probable error when there are few mineral species and a larger but still acceptable probable error as the number of mineral species increases. Expressed numerically the probable error would be 2 percent for minerals constituting 80 percent of the total number of grains, 15 percent for minerals present in amounts of 5 percent, and 40 percent for grains present in amounts less than 5 percent. In some samples there were fewer than 400 grains and the probable percent of error is greater. A Clay-Adams laboratory counter was used to register the counts.

Tables

Table 2 lists the minerals present by sample and, where significant, variation. Quantities are expressed in terms of percent of the total number of nonopaque mineral grains. The total number of grains from which the percentages were calculated is stated. The sample depths given are calculated from the Kelly bushing of the drilling rig and are not recalculated in terms of mean sea level. The column labeled "Remarks" includes any statements of special significance such as roundness, angularity, etching of grains, etc. A heavy-mineral zone is designated for each sample. The following zone abbreviations are used in the table:

Zone	Abbreviation
Rounded tourmaline	RT
Prismatic tourmaline	PT
Augite-muscovite	A-M
Zoned zircon	ZZ
Euhedral zircon	EZ
Glaucophane-hornblende	Gl-H
Biotite	B
Rounded grain	RG

Table 2. Heavy mineral composition of well samples by percent

Well Name - South Barrow Test Well No. 1

Sample depth (in feet)	165	1907	3073	3115	3132	3152	3175	3330	
Heavy-mineral zone	Gl-H	ZZ	ZZ	ZZ	ZZ	ZZ	ZZ	ZZ	
Garnet	35	85	4	14		6	4	16	
Zircon	5	11	33	42	16	57	28	24	
Tourmaline									
brown	6	1	22	20	37	19	31	26	
green	3	1	30	21	45	18	33	33	
blue									
Leucoxene							1		
Biotite	10								
Muscovite	22								
Chlorite									
Andalusite	11								
Chloritoid	3	1	6	4					
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene									
Hornblende									
Glaucophane	3								
Titanite									
Total percent	98	99	95	97	97	100	97	99	
Total grains counted	300	447	68	60	60	303	61	104	
Remarks		Large pink fractured garnet grains Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	

Table 2. Heavy mineral composition of well samples by percent

Well Name - South Barrow Test Well No. 2

Sample depth (in feet)	1299	1762	1784	1999	2047	2056	2111	2126	2170
Heavy-mineral zone	ZZ?	ZZ?	ZZ?	ZZ	ZZ	ZZ	ZZ	ZZ	ZZ
Garnet	75	33	39		5	1	6	6	1
Zircon	1	1		9	7	6	23	27	41
Tourmaline									
brown	1	3	2	26	35	45	29	24	25
green	2	4	2	34	50	47	39	40	31
blue									
Ilmenite									
Biotite		20	8						
Muscovite									
Chlorite									
Andalusite	14	26	29	21					
Chloritoid	6	4	16						
Epidote									
Zoisite									
Rutile									
Anatase				10					
Pyroxene									
Hornblende		4							
Glaucophane									
Titanite									
Total percent	99	95	96	100	97	99	97	96	93
Total grains counted	204	340	490	330	224	410	191	194	292
Remarks	Large pink garnet grains			Zoned zircon Anatase may be authigenic	Zoned zircon		Zoned zircon	Zoned zircon	Zoned zircon

Table 2. Heavy mineral composition of well samples by percent

Well Name - South Barrow Test Well No. 2 (cont'd)

Sample depth (in feet)	2176	2183	2227	2229	2254	2283	2328	2330	2383
Heavy-mineral zone	ZZ	ZZ	ZZ	ZZ	ZZ	ZZ	ZZ	ZZ	PT
Garnet	3	4		5	6	16	91	4	T
Zircon	36	19	74	18	19	28	3	25	3
Tourmaline									
brown	21	33	10	37	32	25	2	32	25
green	33	44	14	38	40	29	2	38	33
blue									
Staurolite									
Biotite									
Muscovite									37
Chlorite									
Andalusite									
Chloritoid									
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene									
Hornblende									T
Glaucophane									
Titanite									
Total percent	93	100	98	98	97	98	98	99	98
Total grains counted	216	155	137	230	370	200	262	158	166
Remarks	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon	Etched clear and pink garnet grains	Zoned zircon	Hornblende grains weathered Tourmaline grains prismatic

Table 2. Heavy mineral composition of well samples by percent

Well Name - South Barrow Test Well No. 3

Sample depth (in feet)	1405	2430	2651	2675	2698				
Heavy-mineral zone	ZZ	RT	RT	RT	RT				
Garnet	20								
Zircon	17	16	7	6	3				
Tourmaline									
brown	27	44	42	34	65				
green	25	40	51	56	31				
blue									
Picotite	T								
Biotite									
Leucoxene	9								
Chlorite									
Andalusite	1								
Chloritoid									
Epidote				1					
Zoisite									
Rutile									
Apatite									
Pyroxene				2 *					
Hornblende									
Glaucophane									
Titanite									
Total percent	99	100	100	99	99				
Total grains counted	300	100	200	300	400				
Remarks	Zoned zircon	Tourmaline grains rounded	Tourmaline grains rounded	Tourmaline grains rounded * augite	Tourmaline grains rounded				

Table 2. Heavy mineral composition of well samples by percent

Well Name - Simpson Test Well No. 1

Sample depth (in feet)	130	378	463	753	940	1297	2748	6173	
Heavy-mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	ZZ	PT	
Garnet	12	44	3	49	31	10	33	3	
Zircon	10	5	5	2		2	13	24	
Tourmaline									
brown	2	7	6	2	7	7	5	21	
green		8	5	4	12	4	3	32	
blue									
Picotite	3	1	1	1	3	3	2		
Biotite	18	5	19	20	19	10	7		
Muscovite	17	13	36	5	3	6	24	8	
Chlorite									
Andalusite	7	2	3	8	10	7	1		
Chloritoid	10		4	1	3	12	2		
Epidote									
Zoisite									
Rutile	1	4	6		1		2	1	
Anatase									
Pyroxene									
Hornblende	1	2	3		4	2	2	10	
Glaucophane	16	3	5	3	3	2			
Titanite									
Total percent	98	96	97	96	98	102	96	99	
Total grains counted	149	192	140	407	263	254	279	145	
Remarks	Garnet grains etched 4:1 zircon	Garnet grains etched 4:1 zircon	Garnet grains etched 4:1 zircon	4:1 zircon			Zoned zircon	Ovoid zircon, tourmaline prismatic bleached hornblende	

Table 2. Heavy mineral composition of well samples by percent

Simpson Core Test

Well Names	No. 1			No. 2		No. 3			
Sample depth (in feet)	45	228		170		273	293	308	338
Heavy-mineral zone	RG	Gl-H		Gl-H		Gl-H	Gl-H	Gl-H	Gl-H
Garnet	27	81		39		78	66		71
Zircon	6	5				2	6		3
Tourmaline									
brown	3			4			5		
green				2			1		
blue									
Picotite	5								
Biotite								59	
Muscovite				25		3	10	26	10
Chlorite								10	
Andalusite	23			9		7	4	2	3
Chloritoid									
Epidote	17	13		9		7	4		10
Zoisite									
Rutile	1					1	2		2
Anatase									
Pyroxene									
Hornblende	7			6					
Glaucophane	15	T		3					
Titanite									
Total percent	99	99		97		98	98	99	99
Total grains counted	193	138		248		250	188	237	196
Remarks	Grains rounded	Grains angular 4:1 zircon		Angular grains		Angular grains Garnet grains etched	Angular grains Garnet grains etched	Some biotite plates are a light rust color	Angular grains Garnet grains etched

Table 2. Heavy mineral composition of well samples by percent

Well Names	Simpson Core Test No. 4				No. 6				No. 7
Sample depth (in feet)	81	103	121		29	45	129		372
Heavy-mineral zone	Gl-H	Gl-H	Gl-H		RG	RG	Gl-H		Gl-H
Garnet	66		11		12	17	35		16
Zircon	2				1		2		3
Tourmaline									
Brown						2	1		4
Green						2			1
Blue									
Picotite									
Biotite	1	24	2				4		31
Muscovite	2	27	2		1		10		19
Chlorite									
Andalusite	5	13	10		8	21	12		21
Chloritoid	1	7	2				2		
Epidote	15	10	41		65	29	3		
Zoisite									
Rutile	2		10			2	2		2
Anatase									
Pyroxene	1 *		2 *						
Hornblende	1	3	19		2	12	2		
Glaucophane	2	13	2		7	13	14		T
Titanite									
Total percent	98	97	101		96	98	95		97
Total grains counted	300	240	200		355	300	333		247
Remarks	Angular grains * augite	Angular grains	Angular grains * augite		Rounded grains	Rounded grains	Angular grains		Angular grains

Table 2. Heavy mineral composition of well samples by percent

Simpson Core Test

Well Names	(	No. 8	)			(	No. 9		)
Sample depth (in feet)	50	210	530			20	40	70	230
Heavy-mineral zone	RG	Gl-H	Gl-H			RG	RG	Gl-H	Gl-H
Garnet	50	49	46			21	16	19	75
Zircon	14	8	5			4	8	T	T
Tourmaline									
brown		2	3					T	
green			4						
blue									
Picotite						1			
Biotite									
Muscovite		10					2		
Chlorite									
Andalusite	14	16	23						
Chloritoid		4				1		11	
Epidote		2	15			67	74	39	
Zoisite									
Rutile			2						
Anatase									
Pyroxene									
Hornblende	20	4				4		16	25
Glaucophane			T				T	2	T
Titanite									
Total percent	98	97	98			99	100	98	100
Total grains counted	140	235	200			154	238	180	160
Remarks	Rounded grains	Angular grains Etched garnet	Angular grains Etched garnet			Rounded grains	Rounded grains	Angular grains	Angular grains

Table 2. Heavy mineral composition of well samples by percent

Well Names - Simpson Core Test No. 10

Sample depth (in feet)	50	90	120	210	250	320			
Heavy-mineral zone	RO	Gl-M	Gl-M	Gl-M	Gl-M	Gl-M			
Garnet		40	61	87	44	23			
Zircon				4	7	1			
Tourmaline:									
brown	T				1				
green						1			
blue									
Picotite									
Biotite					3	5			
Muscovite					1	9			
Chlorite									
Andalusite					29	26			
Chloritoid					3	11			
Epidote	95	44				15			
Zoisite									
Rutile		4	7		1	1			
Anatase									
Pyroxene									
Hornblende	T	12	30	8	9	3			
Glaucophane			T	T	T	3			
Titanite									
Total percent	95	100	98	99	98	98			
Total grains counted	284	250	130	240	362	360			
Remarks	Rounded grains	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet			

Table 2. Heavy mineral composition of well samples by percent

Well Name - Simpson Core Test No. 13

Sample depth (in feet)	610	692	700	749	774	783	893	947	1066
Heavy-mineral zone	B	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	4	37	7	67	62	46	36	14	45
Zircon		2	2	2	T	4	4	1	9
Tourmaline									
brown		2	2	2	T	2	1	3	2
green			3	1				1	1
blue									
Picotite			3	T	2	T			T
Biotite	93	3	26	2	T	10	4	26	3
Muscovite		3	40		T	2	4	6	24
Chlorite									
Andalusite	2		3	5	9	4	8	6	6
Chloritoid		3	3	5	4	6	12	30	6
Epidote									
Zoisite									
Rutile				T			T		T
Anatase									
Pyroxene									
Hornblende		5	4	3	4	6	8	6	3
Glaucophane	T	16	7	12	19	20	24	4	T
Titanite									
Total percent	99	101	100	99	100	100	101	97	99
Total grains counted	221	337	422	457	402	431	491	335	348
Remarks	Subhedral rust colored biotite flakes	Angular grains	Angular grains	Angular grains	Angular grains	Angular grains	Angular grains	Angular grains	Angular grains

Table 2. Heavy mineral composition of well samples by percent

Well Name - Simpson Core Test No. 13 (cont'd)

Sample depth (in feet)	1070	1103	1113						
Heavy-mineral zone	Gl-H	Gl-H	Gl-H						
Garnet	52	72	2						
Zircon	2	T	2						
Tourmaline									
brown	1								
green	2								
blue									
Picotite	2								
Biotite	T	T	19						
Muscovite			62						
Chlorite									
Andalusite	T	10	7						
Chloritoid	9	2							
Epidote									
Zoisite									
Rutile	T								
Anatase									
Pyroxene									
Hornblende	15	5	3						
Glaucophane	15	10	2						
Titanite									
Total percent	98	99	97						
Total grains counted	417	547	410						
Remarks	Angular grains	Angular grains	Angular grains						

Table 2. Heavy mineral composition of well samples by percent

Well Name - Simpson Core Test No. 14

Sample depth (in feet)	309	320	468	476	492	496	572	577	606
Heavy-mineral zone	B	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	T	26	19	5	56	49	62	36	17
Zircon		3	5	4	11	6	4	3	10
Tourmaline									
brown	T	2	2	7	2	5	3	7	7
green		5	1	8	3		1	9	7
blue									
Picotite		1	2	T	2			T	2
Biotite	95	18	12	1	15	3	8	2	T
Muscovite		9	17	21	5	10	5	7	19
Chlorite									
Andalusite	T	10	15	22	1	2	9	15	10
Chloritoid		3	9	3			3	6	2
Epidote									
Zoisite									
Rutile			T						
Anatase									
Pyroxene									
Hornblende		7	3	6	3	9	1	T	5
Glaucophane	T	15	15	19	8	12	4	14	18
Titanite									
Total percent	95	99	100	96	98	98	100	99	97
Total grains counted	400	400	400	400	400	400	400	400	400
Remarks	Subhedral rust colored biotite flakes	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet 4:1 zircon	Angular grains Etched garnet 4:1 zircon	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet

Table 2. Heavy mineral composition of well samples by percent

Well Name - Simpson Core Test No. 14 (cont'd)

Sample depth (in feet)	616	707	848	957	981	1213			
Heavy-mineral zone	Gl-M	Gl-M	Gl-M	Gl-M	Gl-M	Gl-M			
Garnet	30	69	41	52	33	15			
Zircon	8	1	4	3	6	8			
Tourmaline									
brown	5	2	4	7	9	6			
green	9	3	5	8	7	5			
blue									
Picotite	T		2	T	1	3			
Biotite	10		4	10	T	5			
Muscovite	13	5	10	7	9	11			
Chlorite									
Andalusite	7	9	10	14	11	19			
Chloritoid	5	2	5	1	6	3			
Epidote									
Zoisite									
Rutile	T								
Anatase									
Pyroxene									
Hornblende									
Glaucophane	15	7	12	7	19	23			
Titanite									
Total percent	102	98	97	102	101	98			
Total grains counted	400	400	400	400	400	400			
Remarks	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet 4:1 zircon			

Table 2. Heavy mineral composition of well samples by percent

Well Names	(No. 15)		Simpson Core Test (No. 16		)		(No. 17		)
Sample depth (in feet)	309		493	527	539		588	624	799
Heavy-mineral zone	B		Gl-H	Gl-H	Gl-H		B	B	Gl-H
Garnet	2		34	26	27		2	1	3
Zircon			4	T					8
Tourmaline									
brown	T		2	1	1				7
green									6
blue									
Picotite			T	T	2				T
Biotite	90		22	8	7		90	93	8
Muscovite	4		2	4	6		1	2	21
Chlorite									
Andalusite			4	6	3		4	2	10
Chloritoid			20	22	18		T	T	15
Epidote									
Zoisite									
Rutile			T						T
Anatase									
Pyroxene					4 *				
Hornblende			2	1	3		T		5
Glaucophane	3		10	26	26		3	1	21
Titanite									
Total percent	99		100	96	97		100	99	104
Total grains counted	400		400	400	400		400	400	400
	Subhedral rust colored biotite flakes		Angular grains Etched garnet	Angular grains Etched garnet	Angular grains Etched garnet * augite		Subhedral rust colored biotite flakes	Subhedral rust colored biotite flakes	Angular grains Etched garnet

Table 2. Heavy mineral composition of well samples by percent

Well Name → Simpson Core Test No. 23 (No. 24)

Sample depth (in feet)	606	807	902			603	702		
Heavy-mineral set	G1-H	G1-H	G1-H			G1-H	G1-H		
Garnet	5	26	13			30	15		
Zircon	2	4	8			6	7		
Tourmaline									
brown	1	3	7			5	3		
green		2	10			4	7		
blue						1			
[illegible]		2	1				2		
Biotite	7	12	5			9	15		
Muscovite		18	9			8	26		
Chlorite	60								
Andalucite		10	12			5	8		
Chloritoid	10	6	7						
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene									
Hornblende			3			6	T		
Glaucophane	12	15	21			24	19		
Titanite									
Total percent	97	98	96			98	102		
Total grains counted	400	400	400			400	400		
	Contaminated by chlorite; Etched garnet	Angular grains; Etched garnet	Angular grains; Etched garnet			Angular grains; Etched garnet; 4:1 zircon	Angular grains; Etched garnet; 4:1 zircon		

Table 2. Heavy mineral composition of well samples by percent

Well Name - Simpson Core Test No. 25

Sample depth (in feet)	714	839	1005	1024	1048	1096			
Heavy-mineral zone	B	Gl-H	Gl-H	Gl-H	Gl-H	Gl-K			
Garnet	3	37	16	85	89	23			
Zircon	T	4	9	2	T		T		
Tourmaline									
brown	T	3	13	3	T	7	T	T	
green		8	11			8			
blue									
Picotite		2	2			T			
Biotite	95	10	15				31	25	5
Muscovite		15	T			19	42	47	3
Chlorite									
Andalusite		6	10	1	3	15	7	5	10
Chloritoid			7	1	1	10	5	3	7
Epidote									
Zoisite									
Rutile			T			T			
Anatase									
Pyroxene									
Hornblende		T	3			5	3	4	
Glaucophane	1	17	11	6	6	11	8	11	26
Titanite									
Total percent	99	102	97	98	99	98	99	101	98
Total grains counted	400	400	400	400	400	400	400	400	400
Remarks	Subhedral rust colored biotite flakes								

Table 2. Heavy mineral composition of well samples by percent

Simpson Core Test

Well Names	(	No. 26	)		(	No. 28	)	
Sample depth (in feet)	170	268	309		1260	1386	2502	
Heavy-mineral zone	B	B	Gl-H		Gl-H	Gl-H	ZZ	
Garnet	1	2	15		83	76	T	
Zircon					1	3	6	
Tourmaline								
brown	T		T		2	4		
green					1	6		
blue								
Picotite								
Biotite	90	92	32					
Muscovite	3	T	27		3		85	
Chlorite								
Andalusite	T	2	10		5			
Chloritoid					T	5	7	
Epidote								
Zoisite								
Rutile								
Anatase								
Pyroxene								
Hornblende			3					
Glaucophane	6	3	16		3	4		
Titanite								
Total percent	100	99	103		98	98	98	
Total grains counted	400	400	400		400	400	400	
Remarks	Euhedral biotite flakes	Euhedral biotite flakes	Angular grains		Angular grains	Angular grains	Flood muscovite plates Zoned zircon	

Table 2. Heavy mineral composition of well samples by percent

Well Name - Fish Creek Test Well No. 1

Sample depth (in feet)	2920	3030	5509	5530	5558	6009			
Heavy-mineral zone	G1-H	G1-H	ZZ	ZZ	ZZ	ZZ			
Garnet	27	25	22	39	45	33			
Zircon	9	2	4	2	4	25			
Tourmaline									
brown	5	10	5	10	11	5			
green			T	2	2	2			
blue									
Picotite				2	T	1			
Biotite	40	13		1	T				
Muscovite	3	9	4	25	20	13			
Chlorite			9						
Andalusite	7	24	35						
Chloritoid	3	6	21	18	17	15			
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene									
Hornblende	2	4		T					
Glaucophane	3	3							
Titanite									
Total percent	99	98	100	99	99	99			
Total grains counted	254	122	400	400	500	500			
Remarks	Grains angular Etched garnet	Grains angular Etched garnet	Grains angular Etched garnet Zoned zircon	Grains angular Etched garnet Zoned zircon	Grains angular Etched garnet Zoned zircon	Grains angular Etched garnet Zoned zircon			

Table 2. Heavy mineral composition of well samples by percent

Well Name - Cumalik Test Well No. 1

Sample depth (in feet)	250	991	1614	1622	1966	2154	2756	3240	3250
Heavy-mineral zone	EZ	EZ	EZ	EZ	EZ	ZZ	ZZ	ZZ	ZZ
Garnet	14	71	17	53	40	73	69	80	65
Zircon	2	2	3	2	5	21	10	13	17
Tourmaline									
brown	41	3	2	11	14	2	5	2	6
green	32	4		6	5	1	2	T	1
blue	T								
Picotite		5		3	8	T	1	T	2
Biotite			41	T	T	T	1	T	2
Muscovite	9	7	2	5	13	T		1	5
Chlorite									
Andalusite			20		T				
Chloritoid	T	7	14	12	10	T	4	2	5
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene									
hornblende		T	1	2	1		4	2	
Glaucophane									
Ilmenite									
Total percent	93	99	100	99	96	97	96	100	103
Total grains counted	400	400	400	400	400	400	187	500	400
Remarks	Etched garnet Zircon 4:1	Etched garnet Zircon 4:1	Etched garnet Zircon 4:1	Etched garnet Zircon 4:1	Etched garnet Zircon 4:1	Zoned zircon	Zoned zircon	Zoned zircon	Zoned zircon

Table 2. Heavy mineral composition of well samples by percent

Well Name - Oumalik Test Well No. 1 (cont'd)

Sample depth (in feet)	3260	3752	3755	9276	9540	9550	9830	10230	10453
Heavy-mineral zone	ZZ	ZZ	ZZ	A-M	A-M	A-M	A-M	A-M	A-M
Garnet	63	6	31	1					
Zircon	21	2	5	6	10		3	19	23
Tourmaline									
brown	4	3	15	33	11	6	30	19	30
green	5		11	21	2	3	25	32	34
blue	T							T	T
Picotite	1	T	1		2			1	4
Biotite	1	42	2		T		1		
Muscovite	1	13	23	15	76	90	32	25	10
Chlorite									
Andalusite		20							
Chloritoid	2	13	5	T					
Epidote									
Zoisite									
Rutile									
Anatase			T						
Pyroxene				24 *	T *	T *	9 *	3 *	1 *
Hornblende			3	1					
Glaucophane									
Titanite			1						
Total percent	98	99	97	101	101	99	100	99	102
Total grains counted	400	400	400	400	200	200	100	100	104
Remarks	Zircon (zoned)		Zoned zircon	* Augite	* Augite	* Augite	* Augite	Some ovoid pink zircon *Augite	Some ovoid pink zircon * Augite

Table 2. Heavy mineral composition of well samples in percent

Well Name - Meade Test Well No. 1

Sample depth (in feet)	2953	2967	4123						
Heavy-mineral zone	FZ	FZ	ZZ						
Garnet	8	20	65						
Zircon	5	5	6						
Tourmaline									
brown	6	28	1						
green	T	17	T						
blue									
Picotite	1	1	2						
Biotite	15		15						
Muscovite	4	4	2						
Chlorite									
Andalusite	43	15	6						
Chloritoid	16	10	2						
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene		1							
Hornblende									
Glaucophane									
Titanite									
Total percent	100	101	102						
Total grains counted	300	200	500						
Remarks	Etched garnet Zircon 4:1	Etched garnet Zircon 4:1	Zoned zircon Etched garnet						

Table 2. Heavy mineral composition in well samples by percent

Well Name - Topagoruk Test Well No. 1

Sample depth (in feet)	304	603	1204	1209	5972	6142	6498		
Heavy-mineral zone	EZ	EZ	EZ	EZ	A-H	A-H	A-H		
Garnet	40	79	89	90	5		1		
Zircon	1	1	T	1	7	4	9		
Tourmaline									
brown	12	4	1	3	17	4	27		
green	6	1		1	7	5	23		
blue					T				
Picotite		2	T	T	4		4		
Biotite	4					21	7		
Muscovite	3	4	3		55	43	17		
Chlorite									
Andalusite	14				T	22	1		
Chloritoid	19	6	4	4	5	1			
Epidote									
Zoisite									
Rutile									
Anatase					T		T		
Pyroxene					T	T	T		
Hornblende	T	T	2						
Glaucophane									
Titanite					T	T	6		
Total percent	99	97	99	99	100	100	100		
Total grains counted	400	400	400	400	400	400	300		
Remarks	Zircon 4:1	Zircon 4:1	Zircon 4:1	Zircon 4:1					

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 1

Sample depth (in feet)	750	765	922	955	1020	1080	1258	1305	1315
Heavy-mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	22	75	59	T	24	29	46	80	49
Zircon	5	3	20	T	25	22	1	3	4
Tourmaline									
brown	8	8		T	26	13	16	2	11
green	T	T		T	3	8	13	2	9
blue									
Picotite	1	T	2		3	6	7		5
Biotite	3								
Muscovite	53	1	9					3	6
Chlorite			*	96 *					
Andalusite			1						
Chloritoid									
Epidote									
Zoisite									
Rutile					1				
Anatase		1	3		3	3	3	1	1
Pyroxene									
Hornblende	3	5	2	T	8	18	11	6	12
Glaucophane	2	4			2	T			
Titanite									
Total percent	97	97	96	96	95	99	97	97	97
Total grains counted	400	400	400	400	400	400	400	400	400
Remarks	Large flakes of muscovite Etched garnet Angular grains	Large flakes of muscovite Etched garnet Angular grains	* Flood of chlorite	* Flood of chlorite	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 1 (cont'd)

Sample depth (in feet)	1335	1345	1350	1355	1365	1375	1383	1403	1409
Heavy-mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	35	40	29	11	72	83	86	17	36
Zircon			9	10	7	7	4	42	
Tourmaline									
brown	36	33	27	32	3	5	3	13	27
green	13	6	9	23	3	1	2	5	18
blue		6	9	2	1				9
Picotite	8		9	11	4	1	1	13	
Biotite								1	
Muscovite	5				1				
Chlorite									
Andalusite	1								
Chloritoid									9
Epidote									
Zoisite									
Rutile									
Anatase	1				2	1	1	2	
Pyroxene									
Hornblende		6	9	3	4	2	3	4	
Glaucophane		6							
Titanite									
Total percent	99	97	101	97	97	100	100	97	99
Total grains counted	400	400	400	400	400	400	400	300	300
Remarks	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains 4:1 Zircon	Etched garnet Angular grains 4:1 Zircon	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 1 (cont'd)

Sample depth (in feet)	1434	1645	1733	1743	1750	1755	1765	1772	1782
Heavy-mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	69		82	50	44	28	42	2	7
Zircon	7	35	7		24	15	3	19	43
Tourmaline									
Brown	9	29	1	33	4	20	30	45	23
Green	3	12	1	8	10	7	24	28	16
Blue					2			3	2
Picotite	1	12	5	8	6	23			6
Biotite									
Muscovite	1								
Chlorite									
Andalusite									
Chloritoid		12							
Epidote									
Zoisite									
Rutile			T			1			
Anatase	4		1			4		3	1
Pyroxene									
Hornblende	4		2		8				
Glaucophane									
Titanite									
Total percent	98	100	99	99	98	98	99	100	98
Total grains counted	400	400	400	400	400	400	400	400	400
Remarks	Etched garnet Angular grains	Etched garnet Angular grains	4:1 Zircon Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 1 (cont'd)

Sample depth (in feet)	1792	2276	2232	2297	2302	2309	2314	2318	2323
Heavy mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	4	76	95	83	93	96	90	85	80
Zircon	39	7	2	8	3			2	
Tourmaline									
brown	27	1	1	2	1				2
green	18			2			1		2
blue	1								
Picotite	7	2	1	2			1		
Biotite								1	
Muscovite									
Chlorite									
Andalusite									
Chloritoid									
Epidote									
Zoisite									
Rutile								1	2
Anatase	3	4		2	2	3	1	3	
Pyroxene									
Hornblende		12	1		3		7	5	12
Glaucophane									
Titanite									
Total percent	99	102	100	99	102	99	100	97	98
Total grains counted	400	400	400	400	400	400	400	400	400
Remarks	Etched garnet Angular grains	4:1 Zircon Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 1 (cont'd)

Sample depth (in feet)	2327	2332	2337	2342	2347	2542	2563	2931	3498
Heavy-mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	ZZ
Garnet	20	5	38	18	8	4	95	60	33
Zircon	27		3		8	16	1	6	55
Tourmaline									
brown		1		9	29	25		4	1
green					18	2			
blue									
Picotite	21				7	8	1	4	1
Biotite	2		3						
Muscovite				18	12				
Chlorite									
Andalusite	2								
Chloritoid								4	8
Epidote									
Zoisite									
Rutile									
Anatase	4								
Pyroxene									
Hornblende	21	95	54	54	17	41	3	18	
Glaucophane								1	
Titanite									
Total percent	97	101	98	99	99	96	100	99	98
Total grains counted	400	400	400	400	400	400	400	400	300
Remarks	Fresh green hornblende Angular grains Etched garnet	Flood green hornblende Angular grains Etched garnet	Fresh green hornblende Angular grains Etched garnet	Fresh green hornblende Angular grains Etched garnet	Fresh green hornblende Angular grains Etched garnet	Fresh green hornblende Angular grains Etched garnet	Fresh green hornblende Angular grains Etched garnet	Fresh green hornblende Angular grains Etched garnet	Zoned zircon

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 1 (cont'd)

Sample depth (in feet)	4168	5995							
Heavy-mineral zone	22	A-M							
Garnet	35	4							
Zircon	52	3							
Tourmaline									
brown	1	2							
green									
blue									
Picotite	2	1							
Biotite		7							
Muscovite	2	53							
Chlorite		25							
Andalusite									
Chloritoid	6								
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene		5 *							
Hornblende	1								
Glaucophane									
Titanite									
Total percent	99	100							
Total grains counted	400	400							
Remarks	Etched garnet Angular grains Zoned zircon	Etched garnet Angular grains * Augite							

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 2

Sample depth (in feet)	400	525	756	770	790	800	824	936	956
Heavy-mineral zone	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H	Gl-H
Garnet	19	71	34	57	70	67	75	89	66
Zircon	10	9		4		2	16	2	
Tourmaline									
brown	21	7	5	17	10	12	4	4	14
green	9	1		9	4	4	2	1	3
blue		1		4	2	1			
Picotite									
Biotite				3		1			
Muscovite	20	2							7
Chlorite									
Andalusite								1	
Chloritoid									
Epidote									
Zoisite									
Rutile									
Anatase	2								
Pyroxene									
Hornblende	8	6	59	3	13	12	1	2	7
Glaucophane		1							
Titanite									
Total percent	97	98	98	97	99	99	98	99	97
Total grains counted	400	400	400	400	400	400	400	400	400
Remarks	Etched garnet Angular grains 4:1 Zircon	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains 4:1 Zircon	Etched garnet Angular grains	Etched garnet Angular grains

Table 2. Heavy mineral composition in well samples by percent

Well Name - Umiat Test Well No. 2 (cont'd)

Sample depth (in feet)	986	996	1015						
Heavy-mineral zone	01-H	01-H	01-H						
Garnet	80	58	65						
Zircon	2	2							
Tourmaline									
brown	4	22	14						
green	2	2	7						
blue			1						
Picotite									
Biotite	1								
Muscovite	3								
Chlorite									
Andalusite									
Chloritoid									
Epidote									
Zoisite									
Rutile									
Anatase									
Pyroxene									
Hornblende	6	13	12						
Glaucophane									
Titanite									
Total percent	98	97	99						
Total grains counted	400	400	400						
Remarks	Etched garnet Angular grains	Etched garnet Angular grains	Etched garnet Angular grains						

Description of minerals

The accessory minerals of the sedimentary rocks studied show some interesting mineralogic features. Some of these features are used to distinguish particular heavy-mineral zones, therefore descriptions of the minerals are given below.

Detrital opaque minerals

In practically all the samples opaque minerals were present. Because of this ubiquitous occurrence they were found to be nondiagnostic as criteria for zones or correlation purposes. The opaque minerals are lucoxene, ilmenite, and magnetite.

Detrital nonopaque minerals

The suite of detrital nonopaque heavy minerals typified an assemblage derived from metamorphic rocks and to a lesser extent from igneous rocks.

Andalusite.—Andalusite grains are elongate prisms terminated by fractures or in some cases a single termination of a complex pyramid. The grains are usually colorless, many have carbonaceous inclusions zonally arranged parallel to the crystallographic *c* axis.

Augite.—Augite grains are pale-olive green. The shape is determined primarily by cleavage. Some of the grains have thin laths protruding from the main core of the grain, others have saw toothed edges which were etched out by intrastratal solutions.

Biotite.—Two types of biotite are present, a light-rust-colored variety and a dark-brown translucent variety. The rust-colored biotite grains are euhedral to subhedral and contain gaseous (?) inclusions. These grains are particularly abundant in the bentonitic beds of the

Seabee member, and therefore may be interpreted as being a product of volcanic activity 2/. The dark-brown biotite grains are subhedral; their edges are lobate and quite tattered. Under crossed nicols they exhibit a "birds-eye maple" appearance.

Chlorite.—Chlorite plates are common in a few of the samples. The plates are light green and have lobate edges. Chlorite is not a characteristic heavy mineral and its presence is probably due to contamination during the separation of the heavy minerals.

Chloritoid.—Chloritoid occurs as euhedral to subhedral plates with numerous inclusions, probably minute minerals or carbonaceous material. The birefringence is weak. Most grains are pleochroic with x = olive green, y = pale blue, z = ? (due to orientation no color for the z ray direction can be observed). Well-centered Bxa interference figures can be obtained, the optic sign is positive and the angle of 2V is low. The relief is very high.

Epidote.—Epidote is present as bright to dull-green, rather clear grains. Centered optic axis interference figures may be observed with most grains, 2V is large, and the optic sign negative.

Garnet.—Both pink and colorless garnet grains are present in Jurassic, Cretaceous, and Quaternary rocks. Although some grains are fractured, the surfaces of most are etched by intrastratal solutions. Both varieties seem equally susceptible to etching. Triassic rocks of the Barrow wells are barren of garnet; its absence here may be attributed in part to removal by action of the intrastratal solutions. Euhedral grains are present but very rare in heavy residues from the upper part of the Topagoruk member.

2/ Krynine, Paul D., Petrology and genesis of the Third Bradford Sand; The Pennsylvania State College Bulletin, Mineral Industries Experimental Station Bull. No. 29, 1940.

Glaucophane.--Glaucophane occurs as elongate prisms the shape of which is determined by cleavage. Grains frequently yield Bxa interference figures; the optic sign is negative with 2V about 40°. Z is inclined to c plus 4°-6°. The mineral is pleochroic with x = colorless, y= violet, and z = blue. The glaucophane is unaltered and is easily identified by its form and pleochroism.

Hornblende.--Hornblende occurs in two varieties, "common hornblende" and "blue-green hornblende" as described by Krumbein and Pettijohn 3/. Each variety is identified by its characteristic pleochroism, the blue-green hornblende is deep blue to green, common hornblende is bright green to greenish brown. The forms of each are similar and are determined by cleavage. At one horizon in Umiat Test Well No. 1 "common hornblende" is extremely abundant. Here the grains are fresh cleavage laths, some having thin needlelike projections. The hornblende grains in the prismatic tourmaline zone are bleached along the edges and cleavage traces.

Muscovite.--Muscovite occurs as thin cleavage flakes which yield good Bxa interference figures with negative optic sign. The edges are lobate and worn. Muscovite has a specific gravity which is slightly less than that of methylene iodide, but it is such a common detrital mineral that it frequently makes up a considerable part of the heavy residue. Its presence in the heavy portion is probably due to contamination.

Picotite.--Picotite, the brown spinel, is distinguished by its deep brown color, isotropism, and very high relief in Canada balsam or in

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3/ Krumbein, W. C. and Pettijohn, F. J., Manual of sedimentary petrography: Appleton-Century-Crofts, Inc. 1938, page 415.

aroclor. The grains are almost opaque in the thick central parts but are translucent on the thinner edges. All grains are marked by conchoidal fractures. A few grains are greenish brown.

Rutile.—Rutile occurs sporadically in traces in some of the samples. The grains are generally elongate deep-reddish-brown subhedra. The relief is very high. Some forms have oblique and longitudinal striations.

Titanite.—Titanite grains are very rare. The birefringence is very high, therefore the mineral shows the same color with crossed nicols as with ordinary light. Because of the high dispersion many grains fail to extinguish with crossed nicols and white light.

Tourmaline.—Tourmaline occurs in several varieties distinguishable by color and dichroism. The varieties can seldom be classified as to species except indicolite, which is blue. The several color varieties are listed below with their characteristic dichroism.

E ray	O ray
light brown	brown (dravite ?)
light green	olive green
mauve	olive green
deep blue	blue black (indicolite)

In the tables the mauve-olive green and the green-olive green varieties are tabulated together. In the triassic sandstones and the Gubik formation olive-green and brown tourmaline grains are well-rounded; in all other sandstones they are prismatic with pyramid terminations on one end and cross fractures on the other. The blue grains are conchoidally fractured flat chips usually oriented parallel to (001). These flat blue grains yield interference figures, but the isochromatic curves are masked by the intense color of the grain. Authigenic overgrowths are common on the brown and olive-green grains. Some grains have ovoid cores which have been secondarily enlarged. The cores are not always the same color or intensity as the surrounding overgrowths. Apparently this enlargement occurred before the grains were eroded and incorporated in the rocks from which the samples were taken.

Zircon.—Several types of zircon grains are present and are useful in establishing heavy mineral zones. In Triassic sandstones the zircon grains are ovoid. This may be the inherent form of the grain or it may be due to rounding during transportation. In the upper part of the Torok formation, the Tuktu member and the lower part of the Topagoruk member many zircon crystals are zoned. The presence of these zoned crystals is the basis for establishing the zoned zircon zone. Such zoned zircon crystals are light yellow or light pink and have length to width ratios of about 3:1. In the upper part of the Topagoruk member long slender colorless zircon crystals with first order prisms and pyramids are the characteristic form. The length to width ratios of these colorless crystals exceed 4:1. They frequently have acicular liquid (?) or gaseous (?) inclusions. Stuby colorless and pink zircon crystals are also present throughout most of the Cretaceous sandstones.

Authigenic heavy minerals

Anatase.—Anatase occurs as light-yellow subhedral tabular grains. Most grains are marked by geometric patterns. The interference figure is uniaxial negative. Whether or not this mineral is authigenic is difficult to determine. The associated grains are fresh fractured fragments with no obvious rounding or wear on the edges; therefore, if the anatase grains are detrital, no evidence of wear should be expected and the grains should have distinct borders. However if the grains are authigenic, the borders would also be distinct. On the basis of grain shape it is not possible to determine whether the anatase grains are authigenic or detrital.

Pyrite.—Small aggregates and larger single crystals of pyrite are ubiquitous. Although a few of the grains may be detrital the majority are authigenic.

Tourmaline.—Authigenic overgrowths on tourmaline grains are described on page 45.

Heavy-mineral zones

Regional zonation

If the lateral persistence of heavy-mineral zones throughout Naval Petroleum Reserve No. 4 can be demonstrated, such a zonation can serve as a useful correlation device. Heavy-mineral zonation has been established and correlations made by using the following criteria: (1) presence of diagnostic minerals or mineral suites; (2) relative abundance of specific minerals; (3) degree of rounding of mineral grains; and (4) distinction as to grain form, such as euhedral zircon crystals with a length to width ratio of 4:1. Eight distinct zones can be recognized: rounded tourmaline zone, prismatic tourmaline zone, augite-muscovite zone, zoned zircon zone, euhedral zircon zone, glaucophane-hornblende zone, biotite zone, and the rounded grain zone. Descriptions and characteristics of the mineral zones are given below.

Rounded tourmaline zone.—A zone of subround to round tourmaline grains marks the Triassic and probably the lower part of the Jurassic sedimentary rocks in South Barrow Test Well No. 3. Several varieties of tourmaline are present—olive green, mauve, brown, and blue. Over 80 percent of the mineral suite is grains of tourmaline. Zircon grains make up the remainder of the suite, and are ovoid, but the roundness may be influenced by the original crystal form as well as by wear during transportation.

Prismatic tourmaline zone.—In the Jurassic rocks of Barrow and Cape Simpson the characteristic heavy minerals are muscovite, zircon, garnet, hornblende, and tourmaline. Zircon grains are ovoid, garnet grains are etched, and hornblende grains are elongate and prismatic. The hornblende is bleached along edges and cleavage traces. Tourmaline grains are olive-green or brown prisms with fractured or pyramid terminations, and constitute over 30 percent of the heavy-mineral suite. Muscovite and zircon grains are abundant. Hornblende and garnet grains are rare.

Augite-muscovite zone.—The augite-muscovite zone occurs in the Torok formation and is recognized in the Umiat, Oumalik, and Topagoruk test wells. Muscovite grains are particularly abundant, zircon and tourmaline grains are common, and augite, andalusite, chloritoid, and garnet grains are common to rare. Even though augite grains are rare in some samples, their presence is significant. The shape of the augite grains is determined by cleavage; thin delicate laths which have suffered little abrasion during transportation protrude from some of the grains. Intra stratal solutions have etched a few of the augite grains and most of the garnet grains. Zircon grains are euhedral and have a length to width ration of about 2.5:1. The tourmaline grains are prismatic.

Zoned zircon zone.—A zone characterized mainly by minerals derived from metamorphic rocks, but particularly by the presence of zoned zircon crystals, is present in part of the Torok formation in the Barrow area, and in the Tuktu member and the lower part of the Topagoruk member. The zoned zircon grains are usually doubly terminated, have a length to width ratio of 3:1, and are yellow or very light pink. Ovoid pink and colorless zircon grains are also present. Other minerals are garnet, tourmaline, picotite, biotite, andalusite, and muscovite. A few tourmaline grains consist of deeply colored ovoid cores enclosed by faintly colored overgrowths with prismatic faces. The core and the overgrowth of an individual grain may be the same color or different colors. Many garnet grains are etched. Other mineral grains are subhedral or angular.

Euhedral zircon zone.—A zone of long euhedral zircon grains occurs in the upper part of the Topagoruk member in the Meade-Oumalik-Topagoruk area. The euhedral zircon grains are colorless and have length to width ratios which exceed 4:1; first order prisms and pyramids are common. Some pink zircon grains are present and they have more complex crystal forms. Garnet, tourmaline, biotite, muscovite, andalusite, picotite, and chloritoid complete the mineral assemblage. Andalusite grains are prismatic, with single terminations of complex pyramids, and many contain carbonaceous inclusions oriented parallel to the c axis. The biotite plates are colored deep brown or light-rust brown.

Glaucophane-hornblende zone.—The base of the glaucophane-hornblende zone is defined by the greatest depth at which glaucophane is encountered (2,981 feet in Umiat Test Well No. 1). The top of the zone is marked by the base of the biotite zone described below. The zone is present in the upper part of the Topagoruk member in the Barrow-Simpson-Fish Creek-Umiat area. The glaucophane-hornblende zone and the euhedral zircon zone are therefore stratigraphic equivalents. The mineral suite of this zone includes garnet, tourmaline, zircon, biotite, muscovite, andalusite, hornblende, glaucophane, epidote, picotite, and chloritoid. Garnet grains are pink or colorless and a majority of them are etched. Glaucophane grains are blue to lavender pleochroic laths with good cleavage. The hornblende laths are pleochroic deep blue-green to green and are rare to common. Both deep brown and light-rust brown plates of biotite are common to abundant but never constitute more than 50 percent of the mineral suite.

Biotite zone.—In the Cape Simpson area a zone containing dark and light-rust brown biotite flakes is present in the Seabee member. The biotite flakes are subhedral to euhedral and prominant in the bentonitic beds of this member, constituting over 90 percent of the heavy-mineral assemblage. The average thickness represented by this zone is 100 feet. The subordinate minerals are glaucophane, zircon, tourmaline, andalusite, muscovite, and chloritoid.

Rounded grain zone.—A zone characterized by well-rounded grains of andalusite, garnet, glaucophane, epidote, chloritoid, biotite, muscovite, hornblende, tourmaline, and zircon is characterisitc of the Gubik formation. The high degree of rounding of the grains and the number of the mineral species present are the criteria for the differentiation from all other zones. Samples of this zone were obtained only from a few of the Simpson core tests.

Figure 1 lists the stratigraphic units, mineral species and their persistence, and the ranges of the heavy-mineral zones.

Figure 1. Chart showing stratigraphic units, mineral species and their persistence and heavy-mineral zones.

Age	Triassic	Jurassic	Cretaceous				Quaternary
Formation	Shublik	Kingak	Torok	Nanushuk group Umiat formation: Tuktu member	Nanushuk group Umiat formation: Topagoruk member	Colville Gr. Shrader Bluff: Seabee member	Gubik
Diagnostic Minerals							
Andalusite			Prismatic	Prismatic	Prismatic + *	Rare	Round
Augite			Rare-common				Round
Biotite				Rare	Rust colored (to Gubik); <50% * +	>90%	
Chloritoid				Subhedral	+ *	Rare	Round
Epidote					Rare +		Round
Garnet		Rare	Etched > fractured	Etched > fractured	Common to abundant + *	Rare	Round
Glaucophane					Rare-common +	Rare	Round
Hornblende		Rare			+		Round
Muscovite		(Kingak to Gubik)	Abundant		+ *	Rare	
Picotite			Rare	Rare	Rare + *		
Tourmaline	>80%; Round	>50%		Common; Prismatic	+ *	Rare	Round
Zircon	Ovoid	Ovoid	Euhedral 2.5:1	Zoned; Ovoid Pink	Euhedral >4:1 * +	Rare	Round
Mineral zone	Rounded tourmaline	Prismatic tourmaline	Augite-muscovite	Zoned zircon	Euhedral zircon *; Glaucophane-hornblende +		Rounded grain

CORRELATIONS OF HEAVY-MINERAL ZONES

Regional heavy-mineral correlations can be made when heavy-mineral zones persist laterally throughout a sedimentary basin. The persistence of zones within the basin is dependent upon the source rocks and their areal extent, weathering, transportation, deposition, facies patterns, and diagenesis. Some heavy-mineral zones in Naval Petroleum Reserve No. 4 are laterally extensive; others are known only in local areas (primarily because equivalent rock units have not been sampled in surrounding areas).

The rounded tourmaline zone is present in South Barrow Test Well No. 3 between 2,430 and 2,690 feet of depth. No other wells penetrate Triassic rocks in which this zone appears and from which samples are available.

The prismatic tourmaline zone occurs in South Barrow Test Well No. 2 at a depth of 2,383 feet, is probably present in South Barrow Test Well No. 3 between 2,100 and 2,300 feet (no samples were taken in this interval), and is represented by one sample in Simpson Test Well No. 1 at 6,173 feet. No other wells have penetrated equivalent rocks.

The augite-muscovite zone can be traced from Umiat Test Well No. 1 at a depth of 5,995 feet to Oumalik Test Well No. 1 between the depths of 5,972 and 6,498 feet. The full vertical limits of the zone may be greater than those stated, as these limits are controlled by the available samples. The northward thinning and gradual pinching out of the beds in which this zone occurs, as represented in the section from Oumalik to Topagoruk, is probably the reason for the absence of the zone in Simpson Test Well No. 1 and the Barrow wells.

The most extensive zone is the zoned zircon zone; it is represented in all but one of the deep test wells. The depths in the various wells in which the zone occurs are tabulated below.

Name	Depth(s) in feet
South Barrow Test Well No. 1	1,907-3,330
South Barrow Test Well No. 2	1,299-2,330
South Barrow Test Well No. 3	1,405-?
Simpson Test Well No. 1	2,360-?
Simpson Core Test No. 28	2,502-?
Fish Creek Test Well No. 1	5,530-6,009
Umiat Test Well No. 1	3,498-4,188
Oumalik Test Well No. 1	2,154-3,755
Meade Test Well No. 1	?-4,123

The zone should also be present in Topagoruk Test Well No. 1 between ?,000 and 4,000 feet, but no samples are available within this interval. Drilling in Simpson Core Test No. 14 was stopped before this zone was encountered; however, it was penetrated by Simpson Core Test No. 28 at a depth of 2,502 feet. In order that figure 2 be more complete, the section from 2,502 feet in Simpson Core Test No. 28 is projected to Simpson Core Test No. 14.

Two zones are stratigraphic equivalents — the euhedral zircon zone and the glaucophane-hornblende zone. The euhedral zircon zone occurs in Meade Test Well No. 1 at a depth of 2,967 feet, in Oumalik Test Well No. 1 from a depth of 250 feet to 1,966 feet, and in Topagoruk Test Well No. 1 from a depth of 304 feet to 1,209 feet. Northward and eastward the zone grades into the glaucophane-hornblende zone in Simpson Test Well No. 1 and Umiat Test Well No. 1 respectively. The glaucophane-hornblende zone is present in South Barrow Test Well No. 1 at a depth of 165 feet, in Simpson Test Well No. 1 from a depth of 130 feet to 1,297 feet, in Simpson Core

Test No. 14 from a depth of 320 feet to 1,213 feet, in Fish Creek Test Well No. 1 from 2,920 to 3,030 feet, and in Umiat Test Well No. 1 from 750 to 2,981 feet. The mineralogical differences between these two zones are attributed to differences in source rocks and their contribution to subsequent deposits within basins of more or less defined limits.

The biotite zone has been identified only in the Cape Simpson area and is discussed in the section dealing with local correlations.

The rounded grain zone occurs only in Simpson Core Test Nos. 1-10; however, the Gubik formation, in which this zone appears, covers much of the Arctic coastal plain. Samples from other wells were not taken. In figure 2 the rounded grain zone has been projected from the Simpson core tests to Simpson Test Well No. 1.

Figure 2 illustrates the regional distribution and correlations of these heavy-mineral zones.

Local distribution and correlation

In local areas correlations among wells can be made by using the major heavy-mineral zones, and in one case, establishing subzones within the major zones. Cape Simpson and Umiat are areas where detailed correlations are possible.

Cape Simpson area

In Simpson Test Well No. 1 and Simpson Core Tests Nos. 1-4, 6-10, the recognized mineral zones are those of the rounded grain zone and the glaucophane-hornblende zone. All the wells start in the rounded grain zone and penetrate the glaucophane-hornblende zone beneath it. Recognition of this contact, based on the degree of rounding, is simple but serves only to define the base of the rounded grain zone (Cubik formation). Lack of equivalent stratigraphic samples precludes the possibility of a more detailed correlation within the glaucophane-hornblende zone. The heavy-mineral zonation of these holes is shown in figure 3.

Correlation of Simpson Core Tests Nos. 13-17, 23-26, and 28 is possible using the biotite zone and the glaucophane-hornblende zone, as shown in figure 4. The contact defined by these two zones marks the unconformity between the upper part of the Topagoruk member and the base of the Seabee member.

Umiat area

Subzones established within the major heavy-mineral zones are used to make detailed correlations in the two Umiat test wells. Table 3 has been constructed so that the samples used for correlation are placed opposite their equivalents. The heavy-mineral subzones are designated U-1, 2, 3, etc., and are briefly described in table 3. Samples in subzones U-4, 6, and 8 proved useful in correlating the two wells. Samples from 824 feet in Umiat Test Well No. 2 and from 1,733 feet in Umiat Test Well No. 1 contain 75-83 percent garnet, 7-16 percent zircon (length to width ratio, 4:1), 4-9 percent brown tourmaline, 1-3 percent green tourmaline, and 1-2 percent hornblende. Samples at 525 feet in Umiat Test Well No. 2 and 1,434 feet in Umiat Test Well No. 1 contain 69-71 percent garnet, 7-9 percent zircon (length to width ratio, 4:1), 7-9 percent brown tourmaline, and 1-2 percent green tourmaline. Samples from Umiat Test Well No. 2 at 400 feet and from Umiat Test Well No. 1 at 1,350 feet contain 19-29 percent garnet, 9-10 percent zircon, and 30-45 percent tourmaline. This accordance of samples is the basis for correlation of Umiat Test Well Nos. 1 and 2 illustrated in figure 5.

Correlation of faulted section, Umiat Test Wells Nos. 1 and 2:—A reverse fault has been recognized in Umiat Test Wells Nos. 1 and 2. R. G. Reese [4] has described the fault as cutting Umiat Test Well No. 1 at 2,045 feet, with a throw of 750 feet, and with the section from 1,300 to 1,900 feet being repeated in the section from 2,045 to 2,700 feet. To substantiate this correlation comparisons of heavy-mineral suites were made. In figure 5 and also in table 3 the section below the fault is shown opposite its supposedly equivalent section. On the basis of the available samples the following heavy-mineral correlations are apparent. Samples from 525 feet in Umiat Test Well No. 2 and from 1,434 feet in Umiat Test Well No. 1 which are placed in subzone U-6 apparently belong to the same subzone as the sample from 2,276 feet in the projected fault section of Umiat Test Well No. 1. The sample at 756 feet in Umiat Test Well No. 2 which is placed in subzone U-5 seems to correlate with the sample from 2,337 feet in the subfault section of Umiat Test Well No. 1. The subzone U-3 sample from 1,792 feet in Umiat Test Well No. 1 seems to correlate with the sample from 2,542 feet in the subfault section in Umiat Test Well No. 1. This close accordance of heavy-mineral samples seems to substantiate the interpretation of the fault in Umiat Test Well No. 1. Correlations of Umiat Test Wells Nos. 1 and 2 and of the faulted section in Umiat Test Well No. 1 are shown in figure 5. Samples were not available to check the fault in Umiat Test Well No. 2.

4/ Reese, R. G.; Arctic Contractors, Inc., personal communication.

INTERPRETATION OF HEAVY MINERALS OF SEDIMENTARY ROCKS OF NORTHERN ALASKA, IN RELATION TO THE GEOLOGIC HISTORY

Triassic

The Triassic sedimentary rocks of northern Alaska are represented by an almost uniform thickness of slightly less than 300 feet of black shale, silty sandstone lenses, limestone and chert. These rocks are known in the subsurface at Point Barrow, Cape Simpson, and Topagoruk Test Well No. 1, and in outcrops in discontinuous exposures from Cape Lisburne to the Sadlerochit Mountains. The known southernmost exposures of Triassic rocks in northern Alaska are approximately along 68° N. lat., and may have been more extensive but are now removed by erosion or buried by post-Triassic thrust faults. In the Upper Triassic (Noric) deposits, the pelecypod, Monotis subcircularis (Gabb) is the most abundant fossil but is not reliable as a criterion for interpreting the depth of the sea bottom. On the basis of lithology and uniformity of thickness, these rocks were probably deposited in a relatively quiet shallow sea. Under these conditions, the major agents of sediment transportation and distribution would be wave action and bottom currents. The net effect of such activity would be the eventual destruction of less resistant mineral grains and abrasion of the more resistant mineral grains to rounded forms. The presence of rounded tourmaline and zircon grains in the Triassic sandstone of South Barrow Test Well No. 3 may be attributed to the above-mentioned processes. The Triassic deposits may even be composed of grains that had already gone through at least one cycle of deposition and were rounded prior to Triassic time.

Thus far, little evidence regarding the source of Triassic rocks has been found. Unfortunately facies patterns of known Triassic rocks, in northern Alaska, do not indicate the probable source area or how far the grains have traveled. One possible source rock, the Neruokpuk schist of possible pre-Cambrian age, crops out 30 miles south of the Sadlerochit Mountains and contains rounded tourmaline and zircon grains. The tourmaline grains are an olive-green variety similar to those found in Triassic sandstone at Point Barrow. Whether or not the Neruokpuk schist was exposed to erosion here or elsewhere during Triassic time is not know; early Cretaceous and younger periods of faulting have brought it to its present position at the surface. The similarity of tourmaline grains in the Neruokpuk schist and the Triassic sandstone at Point Barrow is the only evidence that suggests that the Neruokpuk schist was one of the source rocks of Triassic deposits. Petrology of other pre-Triassic rocks which should also be considered as possible sources is too inadequately known to justify discussion.

Jurassic

In the Point Barrow-Cape Simpson area Jurassic rocks rest conformably on Triassic; deposition apparently was continuous. In the southern Brooks Range area (Baird Mountains), however, orogenic movements began in early Jurassic time. Initial east-trending thrust faults and folds were developed as a result of compressional forces from the south. Rocks involved in this orogenic movement were Triassic clastics, limestone, and chert; Carboniferous-Permian limestone, chert, and clastics; Devonian clastics and limestone; and Silurian and pre-Silurian greenstone schist, mica schist, chlorite schist, quartzite, calcareous schist, and carbonaceous schist. Mafic igneous intrusives and extrusives were emplaced and the area became a landmass. During this time the shoreline regressed slowly northward but probably never extended much farther north than lat. 68°. Along the southern littoral and neritic zones, Jurassic sediments were deposited in angular relationships with Triassic and older rocks. That this orogeny, with its development of a lithologically complex source area, is recorded in the Jurassic clastics in the Point Barrow-Cape Simpson area is demonstrated by the minerals in the heavy-mineral suite--hornblende, garnet, and muscovite. The one sample from 2,430 feet (see fig. 2) in South Barrow Test Well No. 3 from Jurassic sandstone, assigned on the basis of its mineralogic suite and grain shape, to the rounded tourmaline zone, implies that the earlier part of Jurassic sedimentation in the Barrow area was similar to Triassic deposition. The sandstones higher in the Jurassic section, as in South Barrow Test Well No. 2, that contain a greater variety of heavy minerals reflect the delayed, though normal, changes in the source area. Though the grains probably traveled a linear distance of approximately 300 miles they were not subjected to as intense oscillatory action or reworking as were the grains from older Jurassic and Triassic sandstone, as shown by the prismatic tourmaline grains.

Cretaceous

In the area of the present Brooks Range another orogeny that folded and faulted older Jurassic and pre-Jurassic rocks occurred during the interval between Late Jurassic and Early Cretaceous. Mafic intrusions were emplaced. Lower Cretaceous (Okpikruak formation) graywacke-type clastics were deposited unconformably on this structural complex. Northward in Topagoruk Test Well No. 1 the Okpikruak formation shows no significant angular discordance with the Kingak formation. In Oumalik Test Well No. 1 and Topagoruk Test Well No. 1 the Okpikruak formation is represented by interbedded siltstone and shale from which no suitable heavy-mineral concontrates could be prepared.

At the close of Okpikruak time mountain building was renewed in the Brooks Range area. The Baird Mountains granitic intrusives were formed, and major thrust faults and isoclinal folds developed to the north of this intrusive body. The top of the Okpikruak formation is marked by a significant angular unconformity in the northern Brooks Range province and to a lesser extent in the Arctic Foothills province. If Okpikruak sediments were deposited in the Barrow area, they were probably thin and were eroded during this time, inferring the positive nature of the Barrow high. The present aspect of the Barrow high is shown in the cross section (fig. 2).

The Torok formation, a typical greywacke, was deposited on this irregular surface. The Torok formation consists of a southern facies of lensing coarse sandstone and conglomerate that grades northward into inerbedded siltstone and shale and gradually to predominantly shale. Overlying the conglomeratic and sandstone facies is a shale unit (uppermost Torok) that represonts a southward migration of the sea during upper Torok time.

Heavy-mineral samples from the basal sandstone of the Torok formation in Oumalik Test Well No. 1, Topagoruk Test Well No. 1, and Umiat Test Well No. 1 indicate by the appearance of augite, chloritoid, garnet, and andalusite, that Jurassic mafic igneous rocks and earlier metamorphic rocks were exposed to erosion during early Torok time. As erosion proceeded in the southern Brooks Range area, the sea of late Torok time transgressed farther and farther south and covered at least much of the area now represented by the northern Brooks Range. Torok time was terminated by gradual uplift in the Brooks Range, which caused northward regression of the sea.

This regression initiated Nanushuk group deposition in the northern part of the present foothills and coastal plain areas. Although continental facies of the lower part of the Nanushuk group are known to the south, the section represented in all the deep wells is the marine Tuktu member of the Umiat formation. The base of the Tuktu member (basal Nanushuk) and the top of the Torok formation is a gradational contact. Where lithology is similar and faunal control limited or lacking, the precise contact of these two units cannot be stated with certainty. Likewise, the Tuktu member is gradational upward into the Topagoruk member. The source area of the Nanushuk group must have included, in addition to earlier Mesozoic and late Paleozoic rocks, considerable exposures of early Paleozoic metamorphic rocks and more varied types of igneous rocks. The zoned zircon zone, characteristic of the upper part of the Torok formation, the Tuktu member and the lower part of the Topagoruk member, shows a marked increase in the occurrence of chloritoid, andalusite, and garnet—minerals characteristic of dynamically metamorphosed rocks. Picotite may have been derived from either the mafic igneous dikes and sills or metamorphic rocks. The tourmaline grains that have ovoid cores surrounded by overgrowths with fresh crystal faces suggest derivation from old sandstones and metamorphosed sedimentary rocks that had been mineralized. The euhedral tourmaline grains may have been derived from these same rocks as well as from granitic intrusives in the Baird Mountains. The zoned zircon crystals were probably derived from the large silicic igneous bodies and metamorphic rocks in the Baird Mountains. The influx of these various minerals in the upper part of the Torok formation and lower part of the Nanushuk group implies erosion of the various metamorphic rocks of the Baird Mountains, particularly the altered zones adjacent to the large igneous masses, and, at least, border facies of the igneous masses. These larger intrusive rocks, therefore, were first exposed to erosion during this episode. Continued relative regional uplift in the Baird Mountains area resulted in further erosion during late Nanushuk time (upper Topagoruk), and the shoreline during that time, though oscillating, moved northward. Nonmarine (coal) deposits are present as far north as Cape Simpson. As continental facies are not present more than 20 miles north of Umiat, however, the shoreline trend changed from west to nearly northeast from Umiat to Cape Simpson. Factors to which this change may be attributed include: (1) greater relative uplift in the source area west of Umiat than in the eastern area; (2) greater thicknesses of deposits and consequent filling in of the western part of the trough; (3) deposition of Cretaceous sediments in basins south and north of the Endicott Mountains. Coupled with this shift in the shoreline was the development of two sedimentary petrographic provinces in upper Topagoruk time. The Meade-Oumalik-Topagoruk area, which is predominantly nonmarine, is represented by the euhedral zircon zone, and the Umiat-Fish Creek-Simpson area, which is predominantly marine, by the glaucophane-hornblende zone. Although the geographic distribution of these zones is practically coincident with the marine and nonmarine facies patterns, there is no implication that they are so limited; the glaucophane-hornblende zone occurs in nonmarine and marine deposits where they intertongue. Of great significance is the evidence of a new and predominant source rock in the eastern part of the Brooks Range as shown by the occurrence of glaucophane and the "blue-green" hornblende. Directly south of Umiat in the Brooks Range is a belt of metamorphic rocks which include undifferentiated Silurian and Devonian and older schists. In the 1951 field season this area was studied by a Geological Survey field party. The observations of this party and examinations of rock samples by the writer revealed "blue-green hornblende" but no glaucophane-bearing rocks. Three hypotheses may explain the absence of such rocks at the present surface; (1) the glaucophane rocks have been completely removed by erosion; (2) the glaucophane rocks have not yet been identified in the Brooks Range; (3) the glaucophane rocks have been buried by overthrust sheets of different lithologic character during post-Topagoruk time. Of these, the second is the most likely explanation. Without this critical information only broad generalizations can be stated regarding the source rocks of the glaucophane-hornblende zone; that is, that the source area lies within the eastern part of the Brooks Range and consists of metamorphic, igneous, and in part older sedimentary rocks.

The euhedral light-rust-brown biotite grains also present in the glaucophane-blue-green hornblende zone may be volcanic ejecta. Undifferentiated Mesozoic volcanics are known in the Seward Peninsula and in the Alaska Range. The Seward Peninsula volcanics deserve mention as a possible source for the biotite flakes, but no conclusive evidence can be submitted.

In the western area (Meade-Oumalik-Topagoruk Rivers area) sandstones of the upper part of the Topagoruk member are characterized by minerals of the euhedral zircon zone. Euhedral colorless zircon grains with length to width ratios of 4:1 are distinctive of this zone. They were most probably derived from the Baird Maountain granitic intrusive and from greater depths within this body than the zoned zircon grains of the zoned zircon zone. Deeper erosion of the granitic mass is therefore implied during late Topagoruk time.

Differential uplift with the greatest elevation in the area west of Cape Simpson terminated Topagoruk time. A short period of erosion followed after which the area was submerged. The encroaching sea extended a short distance south of Umiat but probably did not cover Point Barrow or the western part of Cape Simpson. Colville group sediments were deposited north and northeast of Umiat. The Seabee member, oldest part of the Schrader Bluff formation, rests unconformably on the Topagoruk member and is composed of black marine shale with some sandy bentonitic beds near the base. Samples from these bentonitic beds contain an abundance of biotite grains and are therefore termed the biotite zone. The biotite grains are light-rust and dark-brown euhedra. Because of their intimate association with bentonitic deposits they were most likely derived from volcanic ejecta. The undifferentiated Mesozoic volcanics of the Seward Peninsula are, again, the only known volcanoes which could have supplied the bentonitic material. As these volcanoes are about 400 miles distant and proof of their activity during this exact time is lacking, a reasonable doubt must be maintained if they are to be considered as a source.

If erosion of pre-Colville group rocks is postulated as contributing the biotite grains, the only possible source would be the upper part of the Topagoruk member. Biotite grains of older (pre-upper part of Topagoruk) rocks are scarce and not of identical variety. Biotite grains in the upper part of the Topagoruk member are not as abundant as in the Seabee member, being less than 50 percent of the heavy-mineral suite, while in the Seabee member they compose over 90 percent of the heavy-mineral suite. Concentration by sedimentary processes is highly unlikely. A volcanic origin is more acceptable, even though a definite source area cannot be demonstrated.

Younger Cretaceous deposits, Tuluga member and the Sentinel Hill member, overlie the Seabee member conformably and in the areas studied are predominantly shale. At the close of the Cretaceous period the Arctic Slope was uplifted. Tertiary continental deposits are restricted to the area east of the Colville River north of Umiat and north and west of the Sadlerochit Mountains. A tertiary orogeny produced broad gentle folds in the Arctic Foothills and Arctic Coastal Plain provinces. In part, these folds were superimposed on older structures.

During the Pleistocene epoch of the Quaternary period glaciers occupied the Brooks Range. Outwash gravels filled valleys along the mountain front and most of the lowlands of the coastal plain area. Locally marine shallow-water deposits are present. In the coastal plain area these marine and nonmarine clastics, with some possible Recent deposits are the Gubik formation. These deposits were derived from all older rocks. Reworking processes were vigorous and grains are well-grounded. The heavy-mineral suite of the Gubik formation includes rounded grains of all mineral varieties and species found in the older rocks.

SUMMARY

Heavy mineral residues from sandstones of test wells and core tests in NPR-4, northern Alaska have been examined. The following criteria have been used in delimiting eight heavy mineral zones: (1) presence of diagnostic minerals or mineral suites; (2) relative abundance of specific minerals; (3) degree of rounding of mineral grains; (4) distinctions as to grain form. Triassic and Lower Jurassic sandstone beds are characterized by a zone of rounded grains of tourmaline and zircon. The prismatic tourmaline zone is characteristic of the upper part of the Jurassic in the Barrow area. In the Cretaceous sedimentary rocks the augite-muscovite zone is representative of the lower part of the Torok formation; the zoned zircon zone is representative of the upper part of the Torok formation, the Tuktu member and the lower part of the Topagoruk member; the euhedral zircon zone and the glaucophane-blue green hornblende zone are representative of the upper part of the Topagoruk member; and the biotite zone is representative of the Seabee member. The Quaternary sediments are characterized by the rounded grain zone.

Some of these zones are known only in local areas, others have been traced throughout the area studied, and local and regional correlations have been made. In Umiat Test Well No. 1 heavy-mineral zones were used to correlate a section repeated by faulting.

The origin and genesis of the various heavy minerals and heavy mineral suites have been interpreted in relation to geologic history.

BIBLIOGRAPHY

Dana, Edward S., A textbook of mineralogy: Ed. William E. Ford, John Wiley & Sons, New York, 1947.

Grout, Frank F., Petrography and petrology: McGraw Hill Book Company, New York, 1932.

Krumbein, W. C., and Pettijohn, F. J., Manual of sedimentary petrography: Appleton-Century-Crofts, Inc., New York, 1938.

Krynine, Paul D., Petrology and genesis of the Third Bradford sand: Pennsylvania State College, Mineral Industries Experimental Station Bull. 29, Pennsylvania State College, Pennsylvania, 1940.

Mertie, J. B., Jr., Geology and gold placers of the Chandalar District: Mineral Resources of Alaska: U. S. Geol. Survey Bull. 773, 1923.

____________ Mountain building in Alaska: Am. Jour. Sci. vol. 20, No. 116, 1930.

____________ and Smith, P. S., Geology and mineral resources of northwestern Alaska: U. S. Geol. Survey Bull. 815, 1930.

Milner, H. B., Sedimentary petrography: Murby and Company, London, England, 2d. edi., 1929.

Payne, Thomas G., Geology of the Arctic Slope of Alaska: U. S. Geol. Survey Oil and Gas Investigations Map OM 126, 1951.

Pettijohn, F. J., Sedimentary rocks: Harper & Brothers, New York, 1949.

Rogers, A. F. and Kerr, P. F., Thin section mineralogy: McGraw Hill Book Company, New York, 1933.

Sindowski, F. K. Heinz, Results and problems of heavy mineral analysis in Germany: Jour. Sed. Petrology vol. 19, No. 1, April 1949.

Smith, Philip S., Areal geology of Alaska: U. S. Geol. Survey Prof. Paper 192, 1939.

____________ Kobuk-Noatak region, Alaska: U. S. Geol. Survey Bull. 536, 1913.

Tickell, Frederick G., The examination of fragmental rocks: Stanford Univ. Press, Stanford Univ., California, 1931.

Winchell, Alexander N., Elements of optical mineralogy: Part II, Description of Minerals: John Wiley and Sons, Inc., New York, 1933.