GEOLOGY AND ORE DEPOSITS OF THE CENTRAL YORK MOUNTAINS,
WESTERN SEWARD PENINSULA, ALASKA

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF GEOLOGICAL SCIENCES
AND THE COMMITTEE ON THE GRADUATE DIVISION
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

GEOPHYSICAL INSTITUTE LIBRARY
UNIVERSITY OF ALASKA, FAIRBANKS

By
Cleo Ladell Sainsbury

August 1965

ACKNOWLEDGMENTS

Abundant help from individuals and the U.S. Geological Survey made this study possible.

C. F. Park, Jr., was my advisor, and his admonition that this study "was an economic one and should find ore" contributed greatly to the orientation of the mapping toward the search for ore and resulted in the discovery of several new and large deposits of beryllium. Professor K. B. Krauskopf offered suggestions concerning the geochemistry of the ore fluids that formed the beryllium deposits, as did Dr. Fred Barker of the U.S. Geological Survey. Dr. Adolf Knopf, who mapped the tin deposits in the area in 1906, gave valuable information, and Dr. Robert H. Compton and Dr. Knopf provided information on lamprophyre dikes and suggested improvements in the discussion of the igneous rocks.

The field mapping and laboratory work was done under employment by the U.S. Geological Survey, and most of the analyses used herein were made by Survey analysts on samples prepared by the writer. Special thanks are due John C. Hamilton for spectrographic analyses, and to L. F. Rader for chemical analyses of ores. Rock analyses include work done by Christel L. Parker, Elaine L. Munson, Paul Elmore, Samuel Gotts, Gillison Chloa, Lowell Artis, H. Smith, and Cyrus Feldman, all of the U.S. Geological Survey. Stream sediments and soil samples were analyzed by Claude Huffman, G. L. Skinner, A. J. Bartel and L. F. Rader. Fred Hildebrand made a powder film of diaspore grains handpicked by the author and identified the diaspore. The work of these people provided a large part of the data upon which

many of the conclusions expressed herein are based. In the office, Drs. W. R. Griffiths, D. W. Shaws, and D. E. Lee provided information and provocative discussions on the distribution and geochemistry of beryllium.

The field mapping of the beryllium deposits, and the determination of beryllium in laboratory work, was aided by beryllium detectors designed by W. J. Vaughn, and built by John Olin, of the U.S. Geological Survey.

The photomicrographs reflect the skill of Mr. Ernest Krier, U.S. Geological Survey.

Although the field project was proposed by the writer as a result of his work at the Lost River tin mine in 1953-54, the search for beryllium was largely at the urging of Dr. W. R. Griffiths, U.S. Geological Survey, who noted in 1960 (written communication) that placer concentrates from Star Mountain that were analyzed by the U.S. Bureau of Mines contained highly anomalous amounts of beryllium.

In the field, favors were given by the owners of the Lost River tin mine, Mr. L. Brothe and Mr. T. Pearson, and these favors resulted in the finding of the largest beryllium deposits known to date in the area on patented claims belonging to these men. Other companies and individuals who staked claims on beryllium deposits found by the U.S. Geological Survey on public ground generously gave permission for publication of data from their claims. Especial mention should be made of Pearce Walsh of Home, United States Smelting, Refining and Mining Co., Newmont Mining Co., James F. Brown, John Bronsnick, V. W. Vanderbilt and Fred Panikratz of Fairbanks, United States Steel

Corporation, and Bear Creek Mining Company. Capable help was given by Thomas Smith, Donald Grybeck, James Kelly, and Don Peters, geologic field assistants.

To my wife, Collier, I am indebted for financial support through the time of my attendance at Stanford University. To all the people of Nome and Teller, Alaska, I offer heartfelt gratitude for their constant appreciation for our work, and for their comradeship and hospitality during the long summers away from home.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
TABLES	ix
LIST OF ILLUSTRATIONS.	xi
INTRODUCTION	1
Location.	1
Purpose	1
Scope of this report.	3
Methods of study.	3
Previous work	4
ORIOLOGY.	5
Stratigraphy.	5
Rocks of pre-Ordovician age.	7
Slate of the York region (pCs).	7
Limestone and argillaceous limestone (pCal)	10
Undifferentiated limestone and argillaceous limestone (pOl)	12
Summary of pre-Ordovician rocks.	14
Rocks of Lower Ordovician age.	16
General statement	16
Shallow water facies (Cal).	17
Quiet water facies (Ol)	23
Pinkish limestone and argillaceous limestone. . . .	27
Rocks of Middle Ordovician age	29
Limestone and shale (Oshl).	29
Dark limestone (Odl).	32

	Page
Rocks of Upper Ordovician age.	33
Summary of Ordovician rocks.	33
Rocks of Pleistocene age	34
Structure	35
Thrust faults.	37
Normal faults.	41
Time relations of dikes and faults	46
Age of faulting.	47
Igneous rocks	47
Igneous rocks of pre-Ordovician age.	47
Igneous rocks of Late Cretaceous and Tertiary(?) age.	50
Granite stocks.	50
Dike rocks.	52
Rhyolite dikes	52
Lamprophyres	54
Chemical composition	56
Origin	61
Age.	71
Ore deposits.	72
Tin.	72
Economic importance	72
Geology	74
Beryllium deposits	75
Economic importance	75
General description	76

	Page
Beryllium minerals and paragenetic sequence . .	81
Main deposits	95
Rapid River.	96
Curve Creek.	98
Lost River valley.	99
Tin Creek.	101
Camp Creek	103
Lost River mine.	106
The zonal concept of tin-beryllium deposits . .	108
Ore genesis.	110
Distribution of rare elements	115
Discussion	116
Summary of distribution of the rare elements	125
Economic geochemistry	126
Rare elements in supargene processes	126
Stream sediments.	126
Soils	130
Plants.	131
Summary	135
Water	136
REFERENCES CITED	138
APPENDIX	145

TABLES

	Page
Table 1. Reports published or committed for publication	
elsewhere	145
2. Chemical composition of granites of the western	
Seward Peninsula, Alaska.	53
3. Chemical and normative mineral composition of	
lamprophyre dikes and granite xenolith,	
western Seward Peninsula, Alaska.	pocket
4. Tin and tungsten reserves of the Lost River mine. . .	73
5. Ratio of fluorite to beryllium in ores.	77
5a. Semiquantitative spectrographic analyses of	
beryllium ores, Lost River area, Alaska	78
6. X-ray data of minerals reported for the first	
time from the Lost River area, Alaska	82
7. Mineral assemblages in beryllium ores	91
8. Chemical changes during conversion of limestone	
to fluorite-beryllium ore	94
9. Rare element content in weight percent of selected	
sedimentary and metamorphic rocks	117
10. Rare element content in weight percent of granite	
plutons, and their constituent minerals	pocket
11. Rare element content in weight percent of dike	
rocks	pocket

TABLES, Con't

Page

Table 12. Rare metal content of minerals from contact rocks and ores.	pocket
13. Rare element content in parts per million of selected stream sediments, western Seward Peninsula	pocket
14. Rare element content in parts per million of soil samples, Lost River valley	pocket
15. Change in rare element content in parts per million in ash in bulk tundra clumps with respect to corresponding soil samples, Lost River valley.	pocket
16. Change in rare element content in parts per million in ash of specific plants separated from bulk tundra clumps, Lost River valley.	pocket

LIST OF ILLUSTRATIONS

Figure	Page
1 Map of the western Seward Peninsula showing areas discussed in this report.	2
2 Geologic map and structure sections of the central York Mountains.	pocket
3 Geologic map of the west end of the York Mountains. . . .	8
4 Cleaved, thin-bedded argillaceous limestone that overlies the slate of the York region	11
5 Very thin-bedded limestone of uncertain age exposed about the mouth of Esch Creek	15
6 Clastic limestones in beds of the shallow water facies . .	18
7 Knobby-surfaced limestones of the shallow water facies . .	19
8 Contact between rocks of the shallow water facies and the overlying quiet water facies.	24
9 Beds of pinkish limestone of the uppermost Lower Ordovician rocks.	28
10 Dusky-brown weathering limestone and shale of the Oshl map unit	30
10b Dolomitized flaggy limestones of the lowermost Middle Ordovician rocks	31
11 Stratigraphic record of the main Quaternary events recorded in the York Mountains.	36
12 Diagrammatic cross section through marine terraces near Lost River	36
13 Mint River thrust east of the Mint River.	38

LIST OF ILLUSTRATIONS, Con't

Figure	Page
14 Tectonic breccia near thrust fault, showing dis- oriented blocks of limestone.	39
15 Chevron fold involving medium- to thick-bedded limestone of the Ol map unit.	40
16 Rapid River fault in south tributary of the Kanaugak River.	42
17 Rapid River fault where it enters the drainage basin of Rapid River.	43
18 Banded dolomite that replaced nonmagnesian limestone. .	44
19 Coarse-grained gabbro from sheared dike	49
20 Dike-cemented breccia, Lost River mine area	55
21 Xenolith of granite in lamprophyre dike	57
22 Diagram showing the variation in oxides in igneous rocks	pocket
23 Typical dark dike without xenocrysts.	61
24 Composite lamprophyre dike, showing quartz xenocrysts .	62
24a Composite lamprophyre dike, showing oligoclase xenocrysts.	63
25 Typical dark dike that cuts composite dike.	64
26 Lamprophyre dike from area of beryllium deposits. . . .	65
27 Hornblende lamprophyre from dike in Tin Creek	66
28 Compositional trends in igneous rocks	pocket
29 Compositional trends in igneous rocks of the York Mountains	pocket

LIST OF ILLUSTRATIONS, Con't

Figure		Page
30	Cryptocrystalline veinlet of curdy-white chrysoberyl. .	79
31	Cryptocrystalline veinlet of chrysoberyl and diaspore cutting fluorite-beryllium rock	80
32	Rhythmically-banded skarn from the granite in Tin Creek	84
33	Chrysoberyl separated from fluorite-beryllium ore . . .	85
34	Texture of typical fluorite-beryllium ore	86
34b	Cross section of a nodule from Camp Creek	88
35	Beryllium-fluorite ore from marble in Tin Creek	89
36	Geologic map of the beryllium deposits on Camp Creek. .	pocket
37	Geologic map of the beryllium deposits on Rapid River .	pocket
38	Geologic map showing the relations between ore and structure, Rapid River.	pocket
39	Geologic map of the beryllium and tin deposits in Lost River valley	pocket
40	Geologic map of the tin and beryllium deposits in Tin Creek	pocket
41	Probable configuration of ore localized beneath thrusts	105
42	Distribution of zones, minerals, and elements in zoned tin-beryllium deposits.	109

INTRODUCTION

LOCATION

The area of study encompasses some 400 square miles near the western tip of the Seward Peninsula, Alaska, in the Teller B-5, B-6, C-5, and C-6 quadrangles. In an attempt to establish regional data, especially from granite stocks, other areas were visited and samples taken for analyses. The general areas of interest, and the main area mapped, are outlined on figure 1. Within the area of figure 1 are concentrated the only lode and placer deposits of tin that have produced commercially important amounts of metal in the United States. The tin deposits are associated with biotite granite intrusives that are the extension into Alaska of a long belt of granites, many with associated tin deposits, in eastern Siberia. The belt of known tin deposits, lode and placer, continues eastward through central Alaska.

PURPOSE

In the original dissertation proposal, the stated objectives of this research were: 1. to decipher the structure and stratigraphy of the central York Mountains in order to ascertain the geologic setting of the main tin deposits near Lost River, 2. to apply the information gained from step 1, in conjunction with geochemical prospecting, in a search for undiscovered ore bodies, 3. to determine the geochemical distribution of certain rare elements, particularly Sn, W, Be, Li, F, and B, in the rocks, minerals, and ores of the district, and 4. to decipher the geomorphic history of the area, with particular emphasis on the origin and history of the York Terrace (Bench), a wide surface carved on bedrock, and which is a prominent geomorphic feature throughout the map area.

FIGURE 1 MAP OF THE WESTERN SEWARD PENINSULA, ALASKA, SHOWING
AREAS DISCUSSED IN THIS REPORT

SCOPE OF THIS REPORT

Solution of the original objectives of the study required collection of data too voluminous for total inclusion here. In addition, the discovery of attractive new beryllium deposits, with subsequent demand from private industry for information to help plan and direct physical exploration, required publication of much data that would have been included. The Pleistocene history is being published separately, and is presented here only in abstract. The publications that resulted from this study or that are committed for publication elsewhere are listed in table 1, appendix. This dissertation is confined to data directly related to the ore deposits, to the stratigraphy and structure of the area, and to geochemical data not presented elsewhere.

METHODS OF STUDY

Geologic mapping was done directly upon topographic maps at a scale of 1:40,000. Stations were located by aneroid barometer, and by resection of angles by Brunton compass to prominent topographic features. A base camp was established at the Lost River mine, and field camps were placed by use of a light airplane piloted by the writer, and by weasel (a war-surplus tracked vehicle) or back pack. Mapping was facilitated by Kodachrome slides, and by aerial photographs, as well as by constant aerial reconnaissance. Stratigraphic sections were measured at critical localities, and more than 50 collections of fossils were used to help correlate and date rock units. Many of the fossils, however, are new species, without diagnostic stratigraphic value. Plane table maps were prepared of the main beryllium deposits discovered during the course of field work. In all, field work required approximately 1 month in 1960, and 3 months in each of the years 1961-64.

In the laboratory, rocks were studied by thin sections, by chemical and spectrographic analyses, and by examination of insoluble residues of carbonate rocks. In studying the carbonate rocks, an improved method was developed using the classical staining of calcite, combined with selective leaching of parts of uncovered thin sections to reveal delicate structures normally hidden. The method is being described in the Journal of Sedimentary Petrology (Sainsbury, 1965, in press). In studying beryllium ores, and the distribution of rare elements in individual minerals, pure mineral separations were prepared by standard techniques, supplemented by aluminum chloride leach to remove fluorite. In all cases, X-ray diffractometer patterns were prepared for the identification of minerals, and to check the purity of minerals submitted for analyses. For all minerals reported as identified certainly for the first time in the district, principally beryllium minerals, diffractometer tracings are appended, and the main peaks are indexed in table 6 (in pocket). Opaque ore minerals were studied in polished sections, and identifications were confirmed where necessary by X-ray techniques.

PREVIOUS WORK

Much of the knowledge of the geology and ore deposits of the central York Mountains is based upon work by Brooks, Richardson and Collier (1901), Collier (1902), Knopf (1908, 1910), and Steidtmann and Cathcart (1922). The work of Knopf resulted in excellent descriptions of the occurrence and mineralogy of the tin deposits, and no attempt is made here to repeat Knopf's descriptions. Instead, the writer's work on the new beryllium-fluorite deposits is integrated with Knopf's earlier work to develop a zonal relation of the tin and beryllium deposits.

Needless to say, the writer has benefited greatly from all the previous work, and where disagreements are apparent, the reader should realize these disagreements do not reflect upon the earlier work, but instead reflect merely the advance of knowledge of the area which is based solidly upon the earlier work.

GEOLOGY

STRATIGRAPHY

In previous publications, several workers have discussed the stratigraphy of the rocks of the map area, beginning with Brooks, Richardson, and Collier (1901), Collier (1902), and Knopf (1908). Kindle (1911) discussed both the stratigraphy and the faunal zones of the Port Clarence Limestone, and Steidtmann and Cathcart (1922) presented a more detailed description of the stratigraphy. In these descriptions, certain general statements were in agreement, but each writer pointed out uncertainties about the stratigraphic sequence as well. All early workers were agreed that the oldest rocks of the York region (slates) are pre-Ordovician in age, and that the limestones of the York Mountains (Port Clarence Limestone) are principally Ordovician in age, but some Silurian and Mississippian rocks were included. On the geologic map of Alaska (Dutro and Payne, 1957), the slate assigned to the pre-Ordovician by all previous workers was erroneously re-assigned on extremely tenuous grounds to the Triassic.

With the exception of the confusion in assignment of the slate to the Triassic, the early uncertainty with respect to the stratigraphic succession in the Port Clarence Limestone is explainable on the grounds that thrust faulting in the York Mountains was not recognized. The geologic map (fig. 2) demonstrates that limestones of different ages are

in thrust fault contact, and that limestone and slate locally is in thrust fault contact. Hence, although some reference is made here to earlier discussions, the following description of the stratigraphy is based largely upon the writer's work, and upon fossil determinations made by R. J. Ross, Jr. (U.S. Geological Survey) and Dr. Rousseau Flower (New Mexico Institute of Mining and Technology) on collections made by the writer.

In describing the carbonate rocks, the classification scheme of Folk (1959) is used. Unquestionably, the textures of the limestones change, and certain textures are good indicators of depositional environment. Briefly, the limestones here described, in Folk's terms, are as follows:

Micrite - a very fine grained, even-textured limestone with less than 10 percent of terrigenous material, and which represents solidified microcrystalline calcite ooze.

Pelletal limestone - even-textured limestone composed of rounded or ovoid aggregates of microcrystalline calcite ooze, generally ranging between .03-.08 mm in size, and which are considered to be fecal pellets.

Sparrite - a crystalline limestone with calcite grains exceeding 10 microns in diameter, and generally clear. The sparry calcite probably represents a pore-filling cement.

Rudite - a limestone composed of rounded fragments of limestone in a cement of finer grained calcite. If the rounded fragments came from within the basin of deposition, they are called "intraclasts".

The above terms are often combined to describe mixed rocks, for instance, an intrasparrudite is a rudite with sparry calcite cement between the clasts. A pelsparrite is a pelletal limestone with some sparry cement. For a full discussion of the origin of limestones as exemplified by the texture and composition, as well as the depositional environment, the reader is referred to Folk's paper.

Rocks of pre-Ordovician Age

Slate of the York Region (pOs)

Following earlier workers, Steidtmann and Cathcart (1922, p. 16-17) described the slate that outcrops west of the mapped area, and in the northern half of the area shown in figure 2 (in pocket), as "dark-colored to glistening black graphitic sediments of exceedingly fine grain without prominent bedding", a description that applies only to the slaty parts of the unit generally near major thrust faults. In the area of figure 2, the slate also contains thick beds of graywacke, and carbonaceous phyllitic limestone in addition to the slate. The massive graywacke is slightly schistose in places, but in others, beds of graywacke up to two feet thick are found that are not foliated or recrystallized. West of Skookum Creek, graywacke in beds up to two feet thick forms a sequence at least 200 feet thick, and is underlain and overlain by banded siltstone. Similar beds are seen north of Brooks Mountain, where graywacke is thrust over carbonaceous slate, and although no stratigraphic measurements were made, it is obvious that graywacke and siltstone form a significant percentage of the slate formation. A piece of graywacke typical of that from the area north of the Kanauguk River (fig. 3) consists of angular to subround grains of quartz and feldspar averaging .15 mm in diameter in a matrix of clay

minerals, calcite and carbonaceous matter. Most of the feldspar is plagioclase, some of which is clear, and some of which shows albite twinning. Of the matrix material, calcite is most abundant, and amounts to about 5 percent of the rock. Sporadic grains of white mica impart a crude foliation to the rock, but the poor sorting and stratification on a small scale is a notable characteristic of the graywacke.

The upper part of the slate unit is transitional into the overlying argillaceous limestone through a transitional zone several hundred feet thick which going up-section in the slate consists of black carbonaceous phyllitic siltstone, schistose argillaceous rock which weathers bone-gray, then a strongly laminated, brown-weathering siltstone with lenticular beds of dark-gray to black limestone veined with small white calcite veins, and finally a gray slate about 200 feet thick. These units were mapped separately only in the headwaters of Skookum Creek in order to demonstrate the conformable relation with the overlying limestone.

In earlier publications, considerable discussion was devoted to the relation of the slate to the overlying limestone. Collier (1902, p. 18) considered the limestone of the York Mountains to be unconformable over the slates; Knopf (1908, p. 12) discusses the problem in detail and concludes that the slate grades upward into the Port Clarence Limestone; Steidtmann and Cathcart (1922, p. 21) concluded that in the York Mountains and at Cape Mountain conformable relations exist, although this supposed conformable sequence of limestone over slate involves limestone of Mississippian age at Cape Mountain, and of Lower Ordovician age in the York Mountains. This confusion is caused by two factors (1) lumping of all the limestones of the western Seward Peninsula into one

unit, (2) failure to recognize thrust faults in the areas discussed.

At present, it is definitely established that the slate of the York region is gradational upward into an argillaceous limestone, which, however, is pre-Ordovician in age, and which is not properly considered as part of the Fort Clarence Limestone. This limestone unit is shown on the geologic map as pOal. Near granite, thermal metamorphism has converted the argillaceous limestone to calc-silicate rock (a term used here to apply to all reconstituted carbonate rocks), destroying its color, and making it difficult to separate the various argillaceous limestones. This is especially true of the limestones surrounding Brooks Mountain on the north and east side, where argillaceous limestones of different ages are in thrust contact.

Limestone and Argillaceous Limestone (pOal)

The argillaceous limestone, locally schistose and veined with numerous quartz-carbonate veins and veinlets, overlies the slate conformably or with only minor discordance throughout the area of figure 2. Beds of silty claystone averaging about $\frac{1}{2}$ -1 inch thick are interlayered with beds of fine-grained silty, argillaceous, and dolomitic limestones, which, on fresh fracture are distinctly light olive gray to medium gray in color. Minute cubes of pyrite are abundant locally in the limestone, and the weathering of the pyrite gives a distinct orange-red coloration to slopes underlain by the argillaceous limestone. The argillaceous limestone is moderately to intensely deformed into small-scale folds, and locally displays a cleavage which crosses the bedding (fig. 4). Near faults, the argillaceous limestone is intensely dragfolded. It is everywhere cut by veins and veinlets of quartz and carbonate, the ubiquitous presence of which usually distinguishes it from younger limestones which are lithologically similar.

A typical piece of argillaceous limestone from beneath the thrust fault on the mountain between the headwaters of Lost River and the headwaters of Mint River (page 61-62-63) consists of finely bedded medium dark-gray limestone which in this section is composed of approximately 60 percent of micritic limestone and approximately 40 percent of saccharoidal material, principally clay minerals.

Figure 4. Cleaved thin-bedded argillaceous limestone which overlies the slate of the York region. Exposure is beneath the thrust fault on the western end of the limestone of the York Mountains, at the head of Clear Creek.

Between the Mint River and Shoshone Creek, micritic limestone that is younger than the York unit crops out over an area of some 10 square miles, and is transitional above the red-weathering coal units. Folds of larger scale in these younger limestones trend almost west,

A typical piece of argillaceous limestone from beneath the thrust fault on the mountain between the headwaters of Lost River and the east headwaters of Mint River (specimen 61-ABn-501) consists of finely-banded medium dark-gray limestone which in thin section is seen to consist of approximately 60 percent of micritic limestone and approximately 40 percent of terrigenous material, principally clay minerals, mica, and quartz or chert grains. Except for one mica flake, the terrigenous grains are less than .04 mm in diameter. A few zircons, fragments of pyroxene, and antigorite(?) suggest that mafic rocks were being eroded somewhere within the source area that furnished the terrigenous fragments. Pyrite forms a few isolated grains as well as strings of grains, the weathering of which gives a rind of orange-yellow color on the specimen.

In most of the area of figure 2, as well as in the area east of the mouth of the Kanauguk River (figure 3), and at places as far away as the Don River and Teller Mission, 30 miles east, the red-weathering argillaceous limestone is in thrust contact with younger, fossiliferous rocks of the overlying Fort Clarence Limestone. Because of the crumpling of the beds, and the thrust relations with younger rocks, the thickness of the p0a1 unit is undecipherable. It must, however, be several hundred feet thick. No fossils of any type, or structures suggestive of fossils, have been observed in the argillaceous limestone where shown as p0a1 on the geologic map.

Undifferentiated Limestone and Argillaceous Limestone (p0l)

Between the Mint River and Skookum Creek, unfossiliferous limestone that is younger than the p0a1 unit crops out over an area of some 10 square miles, and is transitional above the red-weathering p0a1 unit. Fold axes of larger folds in these younger limestones trend almost east,

and the larger of these are complicated by numerous and complex minor folds. The rocks contain numerous veins and veinlets of quartz and carbonate. Owing to the complexity, the contact between the p0al and p0l units is not shown everywhere on the geologic map.

The stratigraphic succession in the p0l unit is shown best at the north end of the hill between Mint River and Skookum Creek on the south-facing slope, which is almost perpendicular to the dip of the beds. The red-weathering p0al unit is overlain by about 500 feet of thin-bedded, platy, argillaceous limestone that weathers gray green. The limestone is greenish gray on fresh fracture. The beds above are very thin bedded ($\frac{1}{8}$ - $\frac{1}{4}$ inch) argillaceous and phyllitic limestone which are greenish gray on both fresh fracture and weathered surface. This very thin bedded limestone is about 200 feet thick, and is succeeded by about 700 feet of thin-bedded argillaceous limestone with about 50 percent of clayey layers rhythmically interbedded with medium-gray fine-grained micritic limestone with an occasional knobby surface suggesting stromatolites. This limestone weathers into rounded slopes with a distinct brownish tinge. No fossils were observed in any of the beds below the top of this thin-bedded argillaceous limestone. The argillaceous limestone is transitional over about 150 feet of section into medium- to thin-bedded dolomitic limestone which is brownish gray on fresh fracture, and distinctly brownish on weathered surface. The dolomitic limestone is at least 750 feet thick, and weathers to give blocky plates as much as 2 feet in diameter. In the uppermost part of these rocks, weathered plates occasionally display a faint worm tube cast, or fucoidal mark, which is the first hint of fossils in the section.

From the above description it is seen that in the area north of the mountains west of Mint River as much as 2,300 feet of unfossiliferous limestone overlies the pOal unit. For the most part these beds are characterized by quartz-carbonate veinlets, moderate to intense dragfolding, and total absence of signs of life. These characteristics are deemed sufficient to assign the rocks to the pre-Ordovician, although it is possible that the uppermost beds are equivalent to the lower part of the overlying rocks of earliest Early Ordovician age, which are exposed elsewhere.

Around the mouth of Kech Creek, a tributary of Lost River, a very thin bedded argillaceous limestone outcrops over an area approximately one-half mile across. These rocks (figure 5) are highly contorted and contain some quartz-carbonate veinlets. Their west boundary is a fault dipping gently west, and the east boundary is beneath the alluvium of Lost River. After repeated examination, the writer is unable to assign these rocks definitely, and on the map they are included with the rocks of earliest Early Ordovician age (Oal) that underlie most of Lost River valley in that area. There is a distinct possibility that these rocks are equivalent to the very thin bedded limestone about 200 feet thick that occurs in the rocks of pre-Ordovician age in the area described above between Skookum Creek and the Mint River (page 13). If so, they are probably a window in an unrecognized thrust fault.

Summary of Pre-Ordovician Rocks

The pre-Ordovician rocks described represent a gradual change in deposition from unfossiliferous shale and graywacke through argillaceous limestone into argillaceous limestone and dolomitic limestone with a few worm-tube casts and fucoids in the uppermost

part. The oldest of these rocks are intensely folded, moderately metamorphosed to slate or phyllite, veined with quartz-carbonate veins, and intruded by gabbro. The youngest beds are but slightly folded, completely unmetamorphosed, and sparingly fossiliferous in the upper parts. The time gap represented by them, then, is sufficient for a period of widespread plutonic activity to die out, just the time for the rocks to be deformed and grade schistose, and covered by a thin layer of sediment.

Figure 5. Very thin-bedded argillaceous limestone of uncertain age exposed about the mouth of Esch Creek, a tributary of Lost River.

Within the area mapped by the writer in the general Park area, these lower Devonian limestones have been grouped into three main units, the lowermost of which are transitional downward to the apparent pre-Ordovician rocks just described, and the uppermost of which forms the boundary between lower and middle Ordovician. They are best classified on the basis of their depositional environment.

part. The oldest of these rocks are intensely folded, moderately metamorphosed to slate or phyllite, veined with quartz-carbonate veins, and intruded by gabbro. The youngest beds are but slightly folded, completely unmetamorphosed, and sparingly fossiliferous in the upper part. The time span represented by them, then, is sufficient for a period of widespread plutonic activity to die out, for the intrusives to be deformed and made schistose, and covered by thousands of feet of argillaceous limestone prior to the appearance of the first signs of life. It is entirely possible that this time span covers the Precambrian-Cambrian boundary, the so-called Lipalian Interval, but in the absence of confirmatory proof, such as "absolute" age dates, the rocks can be assigned only to the pre-Ordovician.

Rocks of Lower Ordovician Age

General Statement

In the York Mountains, limestones of Lower Ordovician age compose the bulk of the bedrock. For the most part these limestones dip northward, and when viewed from the air give the impression of a homocline broken only by normal faults. Reports by Brooks, Richardson and Collier (1901, p. 31), by Collier (1902, p. 21), by Knopf (1908, p. 63), and by Kindle (1911, p. 335-349) established the age of the limestone as Ordovician, predominantly Lower Ordovician, with some Silurian. The stratigraphic succession, however, remained a matter of considerable speculation.

Within the area mapped by the writer in the central York Mountains, these Lower Ordovician limestones have been grouped into three map units, the lowermost of which may be transitional downward into the uppermost pre-Ordovician rocks just described, and the uppermost of which spans the boundary between Lower and Middle Ordovician. They are best classified on the basis of their depositional environment.

Shallow Water Facies (Cal)

From the mouth of Lost River westward to the Kanauguk River, a thick sequence of argillaceous limestones with features indicative of a shallow water environment of deposition is exposed continuously in sea cliffs and in stream valleys. These rocks show a gradational change over several thousand feet of section upward from thin-bedded, fine-grained carbonaceous limestones and dolomitic limestones with a few interbeds up to several feet thick of massive dark limestones into rocks of the overlying map unit where the massive beds predominate. The lower, thin-bedded rocks have swash marks, ripple marks, crossbedding, fucoidal marks and abundant rounded clasts of limestone similar in composition to the surrounding rock (figure 6). Where the limestones are markedly crossbedded, they consist predominately of dolomite and terrigenous minerals, elsewhere dolomite is for the most part subordinate to calcite. The massive limestones are calcitic, and locally have a knobby surface strongly suggestive of stromatolites (figure 7). The stromatolites and crossbedding show that the section is right side up throughout the area west of Lost River.

In measured sections at the sea cliff west of Lost River valley, and west of the mouth of Koteebue Creek, the limestone could be grouped into distinctive types. West of Koteebue Creek, 1,064 feet of beds were measured, and grouped roughly into the following types, following the classification proposed by Folk (1959). The percentage of each type is given following the description:

1. Medium-gray, fine-grained argillaceous pelosparrite limestone in beds averaging $\frac{1}{2}$ -1 inch thick which weather light gray. Limestone tends to lensoid (less than one inch) fragments surrounded by films of clay. Tops

Figure 6. Clastic limestone (rudite) in beds of the shallow water facies of the Lower Ordovician limestones.

Flowing spring which breaks the south headwaters of the Kanawake River.

of beds are coated with clayey and carbonaceous films - 20.8 percent.

2. Medium-gray to slightly brownish-gray sparite with bedding indistinct in beds to 12 feet thick - 5 percent.

3. Medium-gray to light-gray, sugary-textured, laminated, cross-bedded, dolomitized, sandy limestone weathering faintly bluish-gray. The laminations weather into ribs, and average bed thickness is

Figure 7. Knobby-surfaced limestone of the shallow water facies of the Lower Ordovician limestones. Exposure is in north-flowing stream which enters the south headwaters of the Kanauguk River.

into blocky plates which display cleavage, fresh marks, etc. (figure 6) - 3.0 percent.

4. Very thin bedded medium-gray to olive-gray argillaceous limestone weathering into curved, yellowish-gray plates less than 1/8 inch thick - 2.7 percent.

of beds are coated with clayey and carbonaceous films - 20.8 percent.

2. Medium-gray to slightly brownish-gray sparrite with bedding indistinct in beds to 10 feet thick - 5 percent.

3. Medium-gray to light-gray, sugary-textured, laminated, crossbedded, dolomitic, sandy limestone weathering faintly brownish gray. The laminations weather into ribs, and average between 1/16 and 1/32 inch thick - 11.2 percent.

4. Medium- to thin-bedded, medium-gray, ruditic limestone that weathers medium-gray, and with numerous rounded white clasts some 1/16 inch in diameter - 8.6 percent.

5. Thin-bedded, medium-gray, dolomitic limestone with curved argillaceous partings as much as 1/2 inch thick. Some beds are faintly laminated and crossbedded. All weather medium gray - 14.3 percent.

6. Massive-bedded, medium-gray, fine-grained, micritic limestone with discontinuous films of clay oriented in all directions. Clay seems weather grayish-orange to pale yellowish-orange - 12.5 percent.

7. Thin-bedded limestone and argillaceous limestone approximately 50 percent clay. Beds average 1/2 inch thick, and alternate regularly from clay to limestone. Weathers into cliffs several feet high with distinctive pale yellowish-orange color - 21.5 percent.

8. Thin-bedded, sugary-textured medium-gray to medium light-gray argillaceous limestone with beds of clastic limestone. Weathers into blocky plates which display clasts, swash marks, scour marks, etc. (figure 6) - 3.0 percent.

9. Very thin bedded medium-gray to olive-gray argillaceous limestone weathering into curved, yellowish-gray plates less than 1/8 inch thick - 2.7 percent.

Although these various types recur throughout the section, there are distinct changes upsection which are noticeable on careful examination, e.g., the crossbedded, laminated dolomitic beds are most common and thickest near the base, the massive beds increase gradually upsection, and the thin-bedded, regularly-alternating limestone and argillaceous limestone (type 7) becomes more abundant and thicker upsection. The scarcity of chert in the thicker beds is extremely diagnostic, for in the overlying units, chert becomes noticeable in the massive beds, and is associated with a color change to light brownish gray. When fault blocks are studied, these criteria can be used to determine roughly what part of the Cal unit is represented, but only if sufficient beds are exposed so that one can be reasonably certain of the changes in the section.

The measured section constitutes but a small part of the Cal unit. A constructed cross section, continuing from the measured section, shows that these Early Ordovician, shallow-water facies beds could be as much as 4,500 feet thick in the area west of the mouth of Lost River.

The lithologic variations seen in thin sections of limestone from the measured section are too numerous to describe completely, but a few typical rocks are described as seen in stained thin sections.

Specimen 61-ASn-36, a laminated, crossbedded, dolomitic limestone from the mouth of Keteesbue Creek, consists of an impure dolomitic limestone containing approximately 40 percent of terrigenous fragments comprising angular to subround quartz, plagioclase, zircon, leucoxene, mica and tourmaline. The dolomite forms isolated rhombs and strings of rhombs, whereas the calcite usually forms connecting patches as well as formless, isolated grains. The terrigenous grains average about .06 mm

in diameter, and the dolomite rhombs .08 mm. The laminations are caused by a faint increase of terrigenous fragments. The rock is classed as a quartzo-feldspathic limy dolomite or dolomitic limestone.

Specimen 61-ASn-1, thin-bedded, medium dark-gray argillaceous and carbonaceous ruditic limestone, faintly laminated, beach, 2½ miles west of the mouth of Lost River. Limestone is fucoidally and ripple marked. Consists of about 80 percent micrite or pelletal calcite, locally recrystallized to sparrite, 15 percent dolomite and 5 percent terrigenous fragments of plagioclase feldspar, quartz, mica, and clay minerals, which surround and cement rounded clasts of micritic or pelletal limestone. The faint laminae are caused by strings of terrigenous fragments which are angular to subround, and which average about .04 mm in diameter. The calcite grains are less than .002 mm in size. An insoluble residue shows several grains of pyroxene. The rock is a rudite composed of rounded fragments of micrite or pelsparrite.

Specimen 61-ASn-26, rhythmically-banded limestone and claystone, upper part of shallow water facies, ridgeline at head of center fork of Koteebue Creek. Clayey bands 1/16 to ¼ inch thick interbedded with light olive-gray, fine-grained limestone averaging about ½ inch thick. Limestone consists of uniformly-sized micrite less than .006 mm in diameter with scattered rounded areas of chert(?) some .06 mm in diameter. Claystone layers contain less than 10 percent calcite and are mostly clay and silt-sized fragments of mica and chert(?).

The main fossils sparingly found in beds of the shallow water facies comprise brachiopods, gastropods, and trilobite fragments. A few beds contain rounded clots suggestive of oolites, and extremely rarely, beds with noticeable fossil fragments are found. All fossils identified to

date are either lowermost Canadian in age, or include forms that range into the Canadian (Lower Ordovician).

The depositional environment of the shallow water facies is adequately shown by the ripple marks, clastic limestones and high percentage of terrigenous fragments. The depositional basin bordered a land mass which furnished detrital quartz, feldspar and such minerals as pyroxene, zircon and leucoxene, along with large amounts of clay. This mineral assemblage suggests that the slates of the York region, with their gabbroic intrusives, were being eroded at places on the land mass which furnished the terrigenous fragments.

Quiet Water Facies (O1)

Conformably above the limestones of the shallow water facies is a thick section of thicker bedded limestones with subordinate thin-bedded limestone and argillaceous limestone, all of which was deposited in quiet water. The transition is gradual over several hundred feet of section, and the contact in any particular area is picked at the first massive limestone that is over thirty feet thick. As some of the massive limestones change thickness laterally, it is probable that the contact as shown on the geologic map is not a single continuous horizon. Nevertheless, the contrast between the two units is unmistakable, and they are easily distinguished except where the upper part of the shallow water facies is faulted against the quiet water facies. The appearance of the transition is shown in figure 8, as exposed on the west wall of the cirque south of the central part of Rapid River.

The basal massive limestones range in color from medium gray to light brownish gray. On fresh fracture they display crystal faces as much as 1/16 inch in size which give a distinctive crystallinity to the

Figure 8. Contact between rocks of the shallow water facies and overlying quiet water facies, cirque south of central part of Rapid River. Shearing along top of first massive bed indicates that the overlying rocks are in thrust contact.

limestone, composed of a mixture of rounded intracrystals of calcite or parallel limestone, dolomite, both radially and concentrically developed, fragments of crinoids(?), and bits of fossil both exposed

rock. They weather into cliffs with an extremely rough, pitted surface. In some beds, faint bedding can be seen, others are massive over dozens of feet. The massive limestone is entirely calcitic, and characteristically contains scattered nodules and lenses of chert.

Interbedded with the massive limestones are thin- to medium-bedded calcitic limestones which lack the ripple marks, swash marks and clastic limestone fragments typical of thin-bedded limestones in the shallow water facies. Many are fucoidally marked, however. In some sections hundreds of feet thick, thin-bedded argillaceous limestone may account for almost half the rock, but the massive interbeds tend to retain a brownish tinge and chert nodules, which distinguishes them from the thicker beds in the shallow water facies. In marked contrast to the fossils in massive limestone in the shallow water facies are the sparing but noticeable cephalopod siphuncles in the quiet water limestones.

Typical specimens of the massive limestone are as follows:

Specimen 61-ASN-27, medium light-gray to light brownish-gray massive limestone from the thick bed shown in figure 8. Consists of round to subround intraclasts averaging about 1 mm in diameter surrounded by clear sparry calcite. The intraclasts are composed of grains or pellets less than .002 mm in diameter. Insoluble residues are almost entirely rounded clots of fine-grained silica and of clear quartz. The rock is an intrasparrudite.

Specimen 63-ASN-229B, medium-gray, sparry, massive limestone, ridge at head of center headwaters of south fork of Cassiterite Creek. Calcitic limestone, composed of a mixture of rounded intraclasts of micrite or pelletal limestone, oolites, both radially and concentrically developed, ostracods(?), fragments of crinoids(?), and bits of fossil hash encased

in clear sparry calcite. Insoluble residue consists of a minute amount of chert, clay minerals and mica. The rock is an oosparrite, and is the only oolitic limestone recognized in the field or in the laboratory.

Numerous other thin sections of massive limestone disclose that these thick beds of the quiet water facies are characterized by a very low amount of terrigenous material and by a very high percentage of calcite. The limestone for the most part is micrite or rudite composed of clasts of micrite (or pelletal limestones) surrounded by clear sparrite. Near faults, the massive limestone is dolomitized over wide areas, which, unless the relation of the dolomitization to faulting is recognized, would lead one to describe the rock as sedimentary dolomite.

The thickness of beds of the quiet water facies has not been determined. In the southwest headwaters of Rapid River, a continuous section of beds 2,435 feet thick was measured, and fitted into 5 types. The types and proportion of each are given below:

Type A - medium-to thin-bedded, fine-grained, conchoidally-fracturing, medium-gray, argillaceous limestone with argillaceous material parallel to beds - 46 percent.

Type B - massive, medium-grained, medium-gray to light brownish-gray sparry, calcitic limestone, locally with chert. Weathers light gray to pinkish gray - 24.3 percent.

Type C - massive, medium-grained, hackly-fracturing, medium-gray, sparry, calcitic limestone, locally with chert - 10 percent.

Type D - medium- to thin-bedded, medium-grained, medium-gray to light brownish-gray, conchoidally fracturing limestone with minor but distinct argillaceous partings parallel to bedding; moderate fucoidal markings. Weathers light gray - 4.8 percent.

Type E - thick-bedded, medium-gray to light brownish-gray limestone with chiplike argillaceous material, locally becoming argillaceous partings - 14.8 percent.

The measured beds lie well above the base of the Ol unit, and a constructed section to the base of the unit shows that approximately 4,000 feet of beds underlie the measured beds. It is possible that minor faults cause repetition of beds, but no faults are known which could cause a repetition of a substantial amount of the 4,000 feet. The total thickness of rocks in the Ol unit in the area southwest of Rapid River is indicated, therefore, as approximately 6,500 feet.

Fossils collected from limestones of the quiet water facies just described include brachiopods from the thin-bedded rocks, and cephalopod siphuncles from the massive beds. To date, all determinations of age fall into the Canadian (Lower Ordovician), or into the early Llanvirn (late Early Ordovician).

During deposition of the quiet water facies, the supply of terrigenous material to the basin of deposition was cut off, and waters became clearer and deeper, as indicated by the cephalopod siphuncles and the lack of shallow water marks, such as crossbedding, ripple marks, and clastic limestone.

Pinkish Limestone and Argillaceous Limestone

At the top of limestones of the quiet water facies is a section of limestone with a distinctive pinkish color on fresh fracture, a large amount of trilobite fragments, and regular bedding (figure 9). These rocks weather light gray to a light bluish gray unlike any of the underlying rocks. These pinkish limestones form the uppermost beds of Lower Ordovician age. They have not been delineated separately on the

...but their color is so distinctive that they cannot be mistaken. The beds of pinkish limestone are about 200 feet thick, and are of importance because they occur in small outcrops in two places, which allows the assignment of overlying dolomitized limestones to the Middle Ordovician (e.g., in the fault block between Lost River and Curve Creek, and north of Anderson Creek on the east boundary).

Beds of middle Ordovician age

Figure 9. Beds of pinkish limestone of the uppermost Lower Ordovician rocks where exposed at the base of the mountain in the west headwaters of the Kanauguk River. Scale shown by pack in lower center.

The limestone is dark-gray limestone which weathers to give smooth slopes without cliffs, and of a distinctive dark yellowish-brown to light yellowish-brown color (figure 10). For several dozens of feet above the shale the gray limestone contains thin partings of black shale. Near the base, the limestone is flatter (figure 11) and contains beds 1/3 to

map, but their color is so distinctive that they cannot be mistaken. The beds of pinkish limestone are about 200 feet thick, and are of importance because they occur in small outcrops in two places, which allows the assignment of overlying dolomitized limestones to the Middle Ordovician (e.g., in the fault block between Lost River and Curve Creek, and north of Anderson Creek on the east boundary of the quadrangle).

A massive bed in the pinkish limestone is seen in thin section to consist of calcite in grains ranging from .008 to .02 mm in diameter, with local areas of clear sparry calcite of coarser grain. Insoluble residues are extremely rare, and consist of twinned plagioclase feldspar. A few curved sections of trilobite glabella are noticeable in the hand specimen.

Fossils collected from the pink limestones unit by Sainsbury and identified by R. J. Ross, Jr., U.S. Geological Survey, are trilobites and graptolites of late Arenig and early Llanvirn age (latest Lower Ordovician). The trilobites are described in the Journal of Paleontology (Ross, 1965).

Rocks of Middle Ordovician Age

Limestone and Shale (Gshl)

Black shale overlies the pinkish limestones conformably and with a contact which is gradational over several tens of feet. The shale is between 20 and 50 feet thick, and is succeeded by a thick section of medium-gray to dark-gray limestone which weathers to give smooth slopes without cliffs, and of a distinctive dark yellowish-brown to dusky yellowish-brown color (figure 10). For several dozens of feet above the shale the gray limestone contains thin partings of black shale. Near the base, the limestone is flaggy (figure 10b) and contains bands 1/8 to

Figure 10. Dusky-brown weathering limestone and shale of the Oshl map unit south of the headwaters of Anderson Creek. The unit is cut off by a fault, and rocks that form mountain top in center background are roughly equivalent to those forming the ridge in the left foreground. View north.

1/4 inch thick of carbonaceous or silty limestones. Some beds contain rounded to reniform clots as much as 1/2 inch across composed of minute grains resembling picritic grains, and some contain discoid lenses of rather light-gray chert. About 200 feet above the base, a 6-foot bed of pinkish limestone similar to that in the pink limestone rocks. The gray limestone is extensively dolomitized near the top, and the dolomite

Figure 10b. Dolomitized flaggy limestones of the lowermost

Middle Ordovician (Llanvirn stage) rocks above the graptolitic shales on the mountain on the southeast flank of the granite of Brooks Mountain.

According to J. R. Nelson, the rocks are probably Middle Ordovician.

In the bluffs, the rocks dip northward at angles from 30 degrees to 50 degrees, and locally are completely dolomitized.

Approximately 1,500 feet of beds are exposed in the bluffs, and these

1/4 inch thick of carbonaceous or silty limestone. Some beds contain rounded to reniform clots as much as 1/2 inch across composed of minute grains suggesting globigerina, and some contain discoid lenses of medium light-gray chert. About 200 feet above the base, a 6-foot bed of pinkish limestone similar to that in the pink limestones recurs. The gray limestone is extensively dolomitized near faults, and the weathered dolomite gives distinctive buff-colored streaks. Fragments of trilobites are common throughout the gray limestones, as are graptolites in the shaly partings.

The pinkish limestone of the Ol unit, and the shale and limestone of the Oshl unit, form isolated patches in an east-west belt across the central part of the York Mountains. All the exposures are cut off on the north by major faults, and the total thickness of exposed beds is 2,400 feet where they form a large hill west of the Mint River (figure 2).

Dark Limestone (Od1)

The youngest Paleozoic rocks of the mapped area occur in the upper klippe on the mountain west of Mint River. Although they consist of medium-bedded medium-gray to dark-gray limestone with some light brownish-gray limestone, both lithologically similar to some of the older limestones, they contain a distinctly different fossil assemblage. A key fossil is *Labyrinthites* sp., as determined by Dr. T. E. Bolton of the Geological Survey of Canada, which, according to Dr. Bolton (written communication, 1964) "are limited to the Ordovician, probably the Middle Ordovician."

In the klippe, the rocks all dip northward at angles from 30 degrees to 50 degrees, and locally are completely dolomitized. Approximately 1,250 feet of beds are exposed in the klippe, and these

are fossiliferous throughout. The fossils that date the rocks as Middle Ordovician were obtained from beds forming the top of the mountain, and are near the top of the exposed beds.

Rocks of Upper Ordovician Age

Limestones of Upper Ordovician age occur in the Don River, some four miles east of the east boundary of figure 2, and have been examined only cursorily by the writer. These rocks were described originally by Kindle (1910), although Collier (1902, p. 21) reported on fossils collected from these rocks and which were determined at that time to be of Lower Silurian age. Several redeterminations of these fossils, the last by W. A. Oliver, Jr., U.S. Geological Survey, in 1964, show that these rocks are of Upper Ordovician age, and have no faunal similarity with the Middle Ordovician rocks described in this report. The Upper Ordovician rocks are not described here, but they are important because they indicate that deposition of limestone continued probably throughout the Ordovician in the area of the York Mountains.

Summary of Ordovician Rocks

In the mapped area, deposition of limestone continued almost unbroken throughout Lower Ordovician time and into early Middle Ordovician time. During this span, beds of limestone and argillaceous or dolomitic limestone aggregating at least 8,000 feet, and possibly 12,000 feet, in thickness were deposited in a marine basin. In earliest Ordovician time, the limestones were deposited in a shallow water environment which received abundant terrigenous material. The basin gradually deepened so that by later Lower Ordovician time, a thin graptolitic black shale was deposited. Following deposition of the black shale, the basin probably shallowed somewhat and limestone was

deposited during at least some of (and probably all of) Middle Ordovician and Upper Ordovician time. Future mapping east of the area of this report can be expected to establish a section of fossiliferous limestone that represents all of Ordovician time. The graptolites collected in this study are readily correlated with those of the European section.

Rocks of Pleistocene Age

Rocks of Pleistocene age occur in the central York Mountains only as scattered patches less than a square mile in area along the inner margin of the York Terrace. The rocks are cemented conglomerates which represent lithified deltaic gravels overlain by continental gravels. In a paper which discusses the Pleistocene deposits, and which will be published in the Proceedings of VII International Congress of the International Association for Quaternary Research, 1965, the conglomerates and other Pleistocene deposits are discussed in detail, and the age assignments are justified on fossil and geomorphic data. Only the main conclusions are summarized here, which is the abstract of the INQUA paper (Sainsbury, in press).

"Two marine terraces are well preserved on the western Seward Peninsula, and both record interglacial sea level stands. The oldest, the York Terrace (York Bench), which is mostly between 175 and 210 meters (560 and 700 feet) above sea level, is of Yarmouth(?) age, as suggested by marine fossils in marine conglomerate on the terrace surface, and by the absence of evidence for a high sea level stand separating it from the next younger terrace, the Lost River Terrace, of Sangamon(?) age. The planed rock surface of the Lost River Terrace stands about 6 meters (20 feet) above sea level, and records a sea level height approximately the same as that of the sea which cut terraces that have been dated as Sangamon at Nome, some 145 kilometers (90 miles) east (Hopkins, Mac Neil and Leopold, 1960). Prior to the cutting of the Lost River Terrace, the York Terrace was uplifted more than 100 meters (328 feet) and warped gently.

In the York Mountains, glacial deposits record two widespread glaciations, both of which are probably Wisconsin in age. The older glacial deposits of the "York Glaciation" were much more widespread than the younger deposits of the "Mint River Glaciation." Much later, in Recent time, a climatic cooling caused ice or snow fillings of north-facing cirques and produced protalus ramparts. At the northwestern

end of the York Mountains, the distribution of limestone drift suggests that an ice sheet occupied lowlands of the southernmost Chukchi Sea and Bering Strait area and forced valley glaciers flowing north from the York Mountains to turn west along the mountain front.

If the minimum amount of uplift of the York Terrace is added to the present depth of water in the Bering Strait, the resulting water depths are so great as to indicate that a seaway existed in the Bering Strait throughout early Pleistocene time, or until the uplift of the York Terrace in Illinoian time. Because uplift probably did not extend as far south as Saint Lawrence Island, it is probable that migration routes for land animals and plants lay well south of the Bering Strait prior to Illinoian time."

The main Pleistocene events recorded by erosional features and deposits in the central York Mountains are summarized in figure 11. A diagrammatical cross section through the marine terraces is shown in figure 12.

STRUCTURE

Throughout the mapped area, the structure of the York Mountains is dominated by imbricate thrust faulting, and by several sets of normal faults, some of which are major faults with vertical displacement exceeding 1,000 feet (Kanauguk Fault). Folds large enough to map are practically restricted to the rocks of pre-Ordovician age, or to the vicinity of low-angle faults. Earlier workers interpreted the geologic structure of the York Mountains as a great, faulted syncline trending north (Steidtmann and Cathcart, 1922, p. 32), based upon the fact that the older slates surrounded the younger Fort Clarence Limestone on three sides. The geologic maps of this report (figures 2 and 3) show clearly that the limestones of Ordovician age are everywhere in thrust-fault contact with the pre-Ordovician rocks. Reconnaissance to the east has shown that this thrust relation holds at least eighteen miles east, and probably farther (personal observation, 1963), from which it is concluded that the York Mountains are carved from a

FIGURE 12 Diagrammatic cross section through marine terraces near Lost River

FIGURE 11 Stratigraphic record of the main Quaternary events recorded in the York Mountains, Alaska

small segment of a series of thrust sheets of much larger extent. The delineation of the extent of thrusting is a challenging problem for the future.

Thrust Faults

On the geologic map, two main thrust faults are named, although several others are shown. The north front of the York Mountains is bounded by the Mint River thrust (figure 13), which locally is a zone of imbricate thrusts. West of the east headwaters of the Mint River, the thrust separates limestone of pre-Ordovician age from limestone of late Early Ordovician age; to the east slate is faulted against late Early Ordovician limestone. Where the thick-bedded limestones of the Early Ordovician sequence are thrust over thin-bedded limestone, the lower plate rocks are intensely dragfolded for several hundred feet below the fault plane. Where thrusts are within thicker bedded limestones, the thrust is often a macrobreccia as much as 200 feet thick (figure 14) that consists of jumbled, angular blocks of limestones often with a high percentage of cavities between blocks. At Camp Creek, such a porous zone has been important in localizing fluorite-beryllium deposits. Unexplainably, the rocks of the upper thrust plates for the most part are but slightly folded, and only locally is major fold structure developed. In the area between the East Fork of Grouse Creek and the headwaters of the Anikovich River, chevron folds are well exposed in upper plate rocks, and these folds involve the thick-bedded limestones of latest Early Ordovician age (figure 15). Elsewhere, the generally north dip of the upper plate rocks is noteworthy (see cross sections, figure 2).

In the south half of the map area, a second major fault (Rapid River fault) dipping south between 25 and 40 degrees is interpreted

Figure 13. Mint River thrust east of the Mint River. Rocks below thrust are red-weathering argillaceous limestone of pre-Ordovician age, those above are of late Early Ordovician age. View east. Brooks Mountain in left background. Dark tundra in center foreground is infolded shale of the Oshl map unit. Cross section B-B', figure 2, passes through folds at right angles.

Figure 14. Tectonic breccia near thrust fault, showing disoriented blocks of limestone.

is a thrust fault, based upon the steepening of beds at the fault plane in this area (Figure 14). The steepening of beds near the fault is a characteristic feature along the Rapid River thrust, and indicates that rocks of the upper plate moved north or northwest. Although the cross sections (Figure 2) would be similar to those of the Rapid River thrust, if this were interpreted as a low-angle normal fault, the steepening of

Figure 15. Chevron fold involving medium- to thick-bedded limestones of the O1 map unit, ridge trending northwest between the headwaters of the Anikovich River and the east headwaters of Grouse Creek. Fold axis is almost horizontal.

In a previous publication (Leahy, 1964, p. 9-10), older literature dealing with faults in the Lost River area was synthesized, and it was shown that three distinct systems of normal faults cut the rocks. Continued geological mapping has shown that these fault systems are of regional extent, and are of great importance in localizing ore

as a thrust fault, based upon the steepening of beds at the fault plane in one area (figure 16). The steepening of beds near the fault is a characteristic feature along the Mint River thrust, and indicates that rocks of the upper plate moved north or northwest. Although the cross sections (figure 2) would be easier to explain if the Rapid River fault were interpreted as a low-angle normal fault, the steepening of beds shown in figure 16 is believed to be diagnostic of northward movement of the upper plate. In addition, the Rapid River fault continues east of Lost River, and although complex, it becomes a flat fault on the hill south of Camp Creek, where another thrust dipping gently southeast lies beneath it. Both faults are believed to be thrusts.

Along much of its length, rocks of the upper plate along the Rapid River fault are dolomitized, giving a sharp color break at the fault (figure 17). The dolomitization, especially in thick-bedded rocks, has created a banded light and dark "zebra rock" that throughout the area is confined to rocks near a major fault (figure 18).

Elsewhere in the map area, thrust faults mark the boundary between thick-bedded limestones and thin-bedded limestones, and it is evident that the thick-bedded limestones were relatively competent, and commonly localized thrust planes, some of which may reflect but minor movement, however.

Normal Faults

In a previous publication (Sainsbury, 1964, p. 9-10), older literature dealing with faults in the Lost River area was synthesized, and it was shown that three distinct systems of normal faults cut the rocks. Continued geologic mapping has shown that these fault systems are of regional extent, and are of great importance in localizing ore

Figure 16. Rapid River fault in south tributary of the Kanauguk River, showing steepening of beds in upper plate. View east.

steepening of granular, water-soluble beds replaced
 by thick-bedded limestone of the Clinton unit. View
 east.

Figure 17. Rapid River fault where it enters the drainage basin of Rapid River. White color above fault plane is caused by weathering of granular, white dolomite that has replaced medium- to thick-bedded limestone of the Ol map unit. View west.

By this new information and forced revision of age assignments of the faults, however, and a new system has been recognized.

In addition to the thrust faults, four sets of normal faults are now recognized. The strongest set strikes N. 35° - 35° E., and individual faults dip vertically or steeply south or north, although south dips prevail. These faults are generally downthrown to the south, with displacements not exceeding a few hundred feet. Most of the dip-slip

ORIGINAL POSITION

slip faults. Most of these faults dip steeply and downthrow to the south.

Figure 18. Banded dolomite ("Zebra rock") that replaced medium-bedded nonmagnesian limestone, bed of Rapid River.

The youngest normal faults, which have the greatest displacement, are controlled by the Kanab and Fork faults. On the Kanab fault, which dips 30° - 60° south, the down-slope is downthrown more than 1,250 feet, for the rocks of the last segment are cut off completely. On the Fork fault, which is well shown on the fork terrace east of Lone

deposits. New information now forces revision of age assignments of the faults, however, and a new system has been recognized.

In addition to the thrust faults, four sets of normal faults are now recognized. The strongest set strikes N. 65° - 85° E., and individual faults dip vertically or steeply south or north, although south dips prevail. These faults are commonly downthrown to the south, with displacements not exceeding a few hundred feet. Most of the dikes in the mapped area are intruded along faults of this system, although the dikes are appreciably younger, and faulting has recurred along some of them.

A second strong system of faults strikes N. 20° - 60° W., with downthrow to either east or west on different faults. This system is expressed particularly well along the south front of the York Mountains west of Lost River. Only a few dikes intrude faults of this system. West of King River, faults of this system cut lamprophyre dikes injected in faults of the N. 65° - 85° E. system.

A third system of faults, some of which are continuous for many miles, and which cut faults of the systems already noted, strikes almost north. Most of these faults dip steeply and downthrow to either side is common. No dikes are known to occur in faults of this system, and no known mineral deposits are localized by them.

The youngest normal faults, and those with greatest displacement, are exemplified by the Kanauguk and York faults. On the Kanauguk fault, which dips 30° - 60° south, the south block is downthrown more than 1,250 feet, for the rocks of the Oshl map unit are cut off completely. On the York fault, which is well shown on the York terrace east of Lost

River, downthrow to the south may amount to 5,000 feet, based on the displacement of the mapped contact between the Qal and Ol units north and south of the fault. Both the York and Kanauguk faults are somewhat arcuate, the overall strike averaging almost east. The Kanauguk fault cannot be placed certainly in the area of the headwaters of Lost River, where the rocks are extensively dolomitized and fractured. Several other faults dipping less than 50° south are known, and these cut and are cut by north-trending faults. For the most part, however, faults of all the other systems are cut and displaced by the Kanauguk and York faults.

Around the granite stocks at Brooks Mountain and in Tin Creek, small faults are developed radially. A few rhyolite and lamprophyre dikes are injected in these faults, and some of the dikes cut the granites.

Time Relations of Dikes and Faults.--Although many dikes have intruded the faults that trend N. 65° - 85° E., many of the dikes continue unbroken across faults of younger systems, proving conclusively that injection of dikes took place after most of the faulting. In the Lost River mine, the Cassiterite dike contains the main tin and tungsten ore shoots, and the ore is cut by a post-mineral normal fault along the dike, which proves recurrent faulting. The faults are important economically because they have been the main channels for ore-forming solutions. Subsequent movement on faults already intruded by dikes shattered the dikes and wall rocks, and provided favorable channels for mineralizing fluids.

Age of Faulting

The thrust faults are intruded by all igneous rocks younger than pre-Ordovician in age. At Brooks Mountain, the granite stock of Late Cretaceous age pierces the Mint River thrust, and as the youngest rocks in the map area are Middle Ordovician in age, the thrusting cannot be dated more closely than post-Middle Ordovician and pre-Late Cretaceous.

Some of the normal faults cut the granite stocks, but none displace geomorphic surfaces of middle Pleistocene age (York Terrace), and in the absence of bedded rocks of Cretaceous or Tertiary age, the normal faulting cannot be dated by stratigraphy more closely than Late Cretaceous to early Pleistocene in age, although much of the normal faulting predated the general epoch of intrusion of plutonic rocks.

IGNEOUS ROCKS

Igneous rocks of pre-Ordovician age

Within the mapped area, the igneous rocks can be grouped by two distinct criteria: one by age (pre-Ordovician or Late Cretaceous-Tertiary(?)), and one by composition (granitic or mafic). East of the map area, nepheline basalt lava flows of Pleistocene age are exposed. The igneous rocks of pre-Ordovician age are restricted to the outcrop area of the slates of the York region, and to the thin-bedded, argillaceous limestone of pre-Ordovician age. These pre-Ordovician igneous rocks form small plugs, sills, and narrow dikes, and most can be classed as medium- to coarse-grained gabbro. They are described by Steidtmann and Cathcart (1922, p. 19) as follows:

"The pre-Ordovician basalt, gabbro, and olivine gabbro are fine- to medium-grained compact rocks which were intruded as dikes, sills and stocks into the slate before the limestone was laid down. They

were folded with the slate and limestone and in general show a marked schistosity due to the development of nearly parallel columns of secondary hornblende. They are remarkably alike in grain, color, composition and alteration, and undoubtedly come from one parent magma."

The gabbro commonly contains small flecks of chalcopyrite and pyrrhotite, and sufficient magnetite to deflect the compass. Mulligan (1959, p. 15) reports chromite in placer concentrates from the west end of the York Mountains; it probably is derived from the gabbro. In the headwaters of the Anikovich River (figure 3) numerous hills are formed of gabbro, and geologic mapping shows that many of the hills are remnants of a sill, or several sills, injected near the top of the slate of the York region. The sills must have covered many square miles in extent. Although the gabbro is abundant in the slates, it is far less abundant in the overlying rocks, for it intrudes the overlying argillaceous limestone in but a few dikes, all of which are cut off by thrust faults.

Microscopic examination of thin sections of gabbro show that the pyroxenes usually have an optic angle of 40° to 60° and, if classified by optic angle and beta index of refraction (Hess, 1941), are augite or ferroaugite in composition (Hess, 1941). The gabbro contains abundant leucoxene, opaque iron ores, and labradorite (figure 19). Locally, near faults, gabbro bodies are sheared and serpentinitised; along some faults the gabbro is extensively replaced by sideritic carbonate.

The abundance of gabbro in the slates, and the dearth of it in the overlying argillaceous limestones, suggests that intrusion of gabbro

Figure 19. Coarse-grained gabbro from sheared dike, west end of the York Mountains. Large augite phenocrysts (A), and titaniferous magnetite, partly altered to leucoxene (black), in groundmass of granulated augite and labradorite. Crossed nicols.

Magnification about 13.5 X. Specimen number 61-ASn-477.

had practically ceased by the time the argillaceous limestone was deposited.

Igneous Rocks of Late Cretaceous or Tertiary(?) Age

The youngest intrusive rocks comprise medium- to coarse-grained stocks of biotite granite, medium- to fine-grained dikes of rhyolite, granite, and rhyolite porphyry, and numerous dark dikes which are here classed as lamprophyres, based upon their chemical composition, and upon other features that are common to many lamprophyre dikes, e.g., fresh appearance coupled with abundant carbonate, sulfide minerals, opaque ores, and high content of potassium (Métais and Chayes, 1962).

Granite Stocks

In the mapped area (figure 2), granite forms two exposed stocks, and one that is known only from subsurface exploration. The stock at Brooks Mountain is a porphyritic biotite granite, locally tourmalinized, in which phenocrysts of orthoclase as much as 2 inches in length are common, and in which the biotite usually contains abnormal amounts of radioactive inclusions. Along joints and fractures, and irregularly, the granite is extensively tourmalinized; at other places, notably along shears, it has been kaolinized. The kaolinized shears often contain hematite, and are faintly radioactive. For the most part, the granite is reasonably homogeneous, although locally the content of biotite increases or decreases, and locally the proportion of phenocrysts of orthoclase increases. The quartz crystals vary from euhedral to subhedral, and all are smoky to faintly amethyst in color. Uranium deposits near this granite pluton are described by West and White (1952), and tin-sulfide deposits by Knopf (1908) and by Steidtmann and Cathoart (1922). The mineralogy of the granite and

associated ore deposits is discussed in detail in these papers, and is not repeated here. For analyses, approximately 100 pounds of granite was obtained by breaking with a sledgehammer into fresh boulders of granite in the stream bed of the creek draining the south side of the granite, and selecting unaltered specimens about a pound or two in weight. All the specimens were crushed and quartered, and a sample taken for analyses.

The granite that forms a small boss in Tin Creek is a medium-grained biotite granite with associated tin deposits (Knopf, 1908) and beryllium deposits (Sainsbury, 1963). The finer grain is probably due to the shallow deroofing of the granite which exposes only the finer grained border facies. Along joints, the granite contains quartz and minor cassiterite; in an irregular area at the northeast end, it is greisenized along fractures, kaolinized locally, and contains cassiterite and numerous sulfide minerals (figure 20). Near lamprophyre dikes that intrude the granite, it is argillized. The sample for analysis was obtained by breaking about 50 boulders in Tin Creek, and taking unaltered specimens about a pound in weight, which were combined, crushed to one-half inch, and quartered.

At Lost River mine, exploratory workings intersect granite that is locally greisenized, and locally only faintly sericitized. The granite has been described by Sainsbury (1960, p. 17-19), and is probably a cupola of a larger body. The granite is a medium- to fine-grained biotite granite, with faint sericitization of the feldspars, and with thin cassiterite-sulfide-mica veinlets along joints. The sample analyzed was a composite one selected from the freshest granite on the mine dump, obtained as waste from an exploration drift in the granite.

Elsewhere on the western Seward Peninsula, biotite granite forms stocks at Cape Mountain, Ear Mountain, and Black Mountain, where, for the most part, the granites are coarse-grained biotite granite, locally tourmalinized, with chilled border facies and with associated cassiterite and sulfide deposits. All were sampled by taking numerous specimens from broken boulders, similar to the method used at Tin Creek and Brooks Mountain.

Chemical analyses of the granites, as determined for this study, are presented in table 2 (following page), from which it is seen that the granites range in silica content from 71.3 to 76.5 percent. The stock in Tin Creek, which has quartz along joints, is the most silicic of the stocks, and the granite dike from Black Mountain is the most silicic rock of those analyzed.

The amount and distribution of trace elements in these granites is shown and discussed on pages 116-122 of this report.

Dike Rocks

Many mafic and rhyolitic dikes, some strongly altered and metasomatized, strike mostly northeast to east and are concentrated in a zone a few miles wide that crosses the mapped area in a direction about N. 80° E. Many of these dikes are intruded along normal faults, a few cut some of the granites, and some radiate from granite, as at Brooks Mountain and Tin Creek. As the dikes mark fractures which have been reactivated, and along which ore solutions rose, they are extremely important in pinpointing possible mineralized areas, and all known dikes are shown on figure 2. Only a few of the dikes are mineralized, however.

Rhyolite Dikes.--The rhyolite dikes range in color from bone white to pale green, and most are composed mainly of quartz, orthoclase and

Table 2. Chemical composition of granites of the western Seward Peninsula, Alaska
 [Analysts: Paul Klawns, Sam Botts, Callison Chioe, Lowell Artis, H. Smith, Cyrus Feldman]

Laboratory analysis	162978	162979	162980	162981	162982	
Field sample	60-ASn-145	60-ASn-90	60-ASn-52	60-ASn-67	63-ASn-145	41-AC-192
Description and location	Granite, Brooks Mountain	Granite, Cape Mountain	Granite, Tin Creek	Granite, Lost River	Granite, Mountain	Granite, Ear Mountain
Type of sample	Bulk chip	Bulk chip	Bulk chip	Bulk chip	Bulk chip	Chip
Type analyses	11/	1	1	1	1	22/
SiO ₂	71.3	73.8	76.5	74.8	74.3	73.93
Al ₂ O ₃	14.4	13.6	12.8	12.9	14.0	14.70
Fe ₂ O ₃	.56	.37	.10	.13	.27	.41
FeO	1.4	1.3	.82	.62	.54	1.40
MgO	.80	.55	.10	.53	.06	.48
CaO	1.1	.87	.44	1.2	.50	.50
Na ₂ O	4.1	3.5	4.1	3.3	3.4	4.27
K ₂ O	5.3	4.8	4.3	4.5	5.6	3.54
H ₂ O-	.18	.00	.26	.55	.00	.00
H ₂ O+	.56	.73	.27	.75	.80	.34
TiO ₂	.21	.18	.02	.01	.13	.12
P ₂ O ₅	.06	.04	.00	.00	.00	.04
MnO	.05	.04	.03	.10	.03	Trace
CO ₂	<.05	<.05	<.05	<.05	<.05	
Sum	100	100	100	99	100	99.92

53

1/ Rapid rock analyses.

2/ Standard rock analysis, by Cyrus Feldman.

albite. Near the tin deposits, as at Lost River mine, the rhyolite dikes have been greisenized, resulting in the loss of Na_2O and K_2O (for analyses, see Sainsbury, 1960, p. 1492). The present study has shown that the material removed during greisenization has moved outward and upward on the dikes, converting the rhyolite to a white rock composed of quartz and adularia, with minute crystals of fluorite. Hence, the present composition of many of the rhyolite dikes is the result of K-metasomatism, the potash having been derived from altered dikes and granites. Some of the dikes cut the granites, as at Brooks Mountain and Tin Creek, and most are injected into fractures of the N. 60° - 85° E. system. The greatest number are concentrated near the stocks, and seemingly are genetically related to them. Locally both rhyolite and lamprophyre dikes are injected along the same fracture, and although the lamprophyres contain xenoliths of granite, no lamprophyre xenoliths have been found in the rhyolites or granite.

Throughout the region, the rhyolite and granite dikes are more continuous and generally thicker than the lamprophyres. Some, such as the Cassiterite and Ida Bell dikes of the Lost River mine area, are more than a mile long, and although some lamprophyre dikes are as continuous, most are lenticular, and form an echelon swarms.

Of especial interest are dike-cemented breccias composed of fragments of limestone and dolomite cemented by coarse-grained granite. One such breccia is shown in figure 20, from which it is seen that the carbonate fragments have reacted only slightly with the enclosing magma, suggesting that the temperature of crystallization was low.

Lamprophyres.--In this study, considerable emphasis was placed upon the dark-colored dikes that are widespread throughout the map area, and

about which little was known previously. These dikes are now believed to be lamprophyres whose chemical composition is a result of contamination of mafic magmas by the incorporation of granite fragments. In some of the dark dikes, composed of coarse-grained granite have been found (figure 21), and thin sections of most show clearly xenocrysts of quartz and

Figure 20. Dike-cemented breccia, Lost River mine area. Medium-grained granite cements fine-grained limestone fragments.

Note spherulitic wollastonite(?) on margins of limestone fragments. Crossed nicols. Magnification about 16 X.

Specimen number 62-ASn-737B.

They are generally composed of the same minerals as those of the host rock, particularly quartz, feldspar, and biotite.

Most of the lamprophyres are dark fine- to medium-grained rocks of granitic appearance. Most appear porphyritic because of the xenocrysts.

Almost all contain pyroxene in two generations, the earliest constituting

about which little was known previously. These dikes are now believed to be lamprophyres whose chemical composition is a result of contamination of mafic magma by the incorporation of granite fragments. In some of the dark dikes, xenoliths of coarse-grained granite have been found (figure 21), and thin sections of most show clearly xenocrysts of quartz and orthoclase feldspar, the size of these xenocrysts in some dikes varying directly as the grain size of the granite they penetrated at depth. For instance, dark dikes near Brooks Mountain contain abundant resorbed xenocrysts of orthoclase as much as an inch in length, whereas elsewhere they are much smaller. In such dikes, the quartz content is relatively high, and the dikes are lighter in color than the uncontaminated lamprophyres. In some areas, as at Tin Creek, dark dikes increase in number near the granite stock; elsewhere, as in Rapid River, a swarm of dark dikes occurs in an area mineralized by fluorite-beryllium veins that grade downward to cassiterite-sulfide deposits that elsewhere are invariably related spatially to granite. Xenoliths of granite are especially common in these dikes. Hence, although lamprophyre dikes extend throughout the area, and locally form small plugs, they are in places particularly numerous near exposed or buried granites, and their mineralogic characteristics show conclusively that they are contaminated rocks. However, they are not genetically related to the granites, as proved by the dissimilar contents of trace elements, particularly beryllium, boron and lithium.

Most of the lamprophyres are dark fine- to medium-grained rocks of fresh appearance. Most appear porphyritic because of the xenocrysts. Almost all contain pyroxene in two generations, the earliest constituting

Figure 21. Xenolith of coarse-grained granite (lower right) in lamprophyre dike on Rapid River. For analyses of xenolith and lamprophyre, see table 3. For trace elements in each, see table II.

The dike is in terms of mineralogic and chemical composition described by Anand (1963) and characterized briefly by Wells and Hayes (1963, p. 12-15). In table 3 (in pocket) are shown the chemical composition and names of several lamprophyres, the names being submitted by the U.S. Geological Survey Branch of Computations, by

STANDARD 14400005
U.S. GEOLOGICAL SURVEY

partly resorbed phenocrysts, and the later being confined to the groundmass, which consists mainly of plagioclase laths, mostly of andesine or labradorite composition, and abundant carbonate, some of which replaces pyroxene and possibly plagioclase. Most contain pyrite, opaque iron ores, and sphene; a few contain areas of chlorite, uraltic hornblende, and serpentine(?) that suggest altered olivine. In some the biotite is distinctly muddy green in the center, which is rimmed with the usual brown biotite, in others the biotite is all brown. All show substantial titania in chemical analyses, and this titania is reflected in either a large amount of ilmenite(?) and leucoxene or in large crystals of sphene (figure 27), much of which is altered badly. Staining by sodium cobaltinitrite solution reveals that in the groundmass, potassium feldspar ranges from almost zero to as much as 15-20 percent, and increases near the granite xenoliths. In short, the lamprophyres exhibit many features common to lamprophyres elsewhere, and their origin is worthy of discussion here. The lamprophyres contain granitic xenoliths, as well as xenocrysts of quartz and orthoclase feldspar, and their origin as contaminated rocks seems reasonably clear.

Chemical composition: Several of the lamprophyre dikes have been analyzed chemically, and are found to be very similar to other lamprophyres, particularly in the high content of CO_2 , H_2O , K_2O , Na_2O , and the low silica content (Métais and Chayes, 1963, p. 156). In this paper, lamprophyres are discussed in terms of mineralogic and chemical groups as discussed by Knopf (1936) and summarized broadly by Métais and Chayes (1963, p. 156-157). In table 3 (in pocket) are shown the chemical composition and norms of several lamprophyres, the norms being calculated by the U.S. Geological Survey Branch of Computations, by

computer. Some of the analyses and therefore the resulting norms would be considered too inaccurate for precise petrology if standards were required as noted by Métais and Chayes (1963, p. 156). However, in this paper, I am attempting to show only that the lamprophyres are contaminated rocks that are genetically related to granite, and the standards of accuracy apply to all the rocks used here, for which analyses appear in table 2. Rocks are listed as they appear in figure 22 from left to right. Below the norms, essential minerals of the mode are listed. Owing to the extremely fine grain of the groundmass of many of the dark dikes, modal analyses were not deemed possible.

The left column in figure 22 shows the chemical composition of a single hand specimen of a lava flow of Pleistocene age from the California river area (figure 2). It is a black fine-grained, vesicular rock locally showing olivine and nepheline. It is plotted to contrast its chemical composition with that of the next most mafic rock (41-AC-66), a black dike similar to those here called uncontaminated lamprophyres (or diabase), and collected by R. R. Coats from the south of the Anikovich River, far from any known or suspected granite (figure 3). There is no similarity between the two rocks.

The next group of dikes, with silica in the range of 53-57 percent, represent dark lamprophyre dikes from areas near granite or near suspected granite at Rapid River, Tin Creek, and Black Mountain. In thin section, it can be seen that all of these rocks contain xenocrysts of quartz and orthoclase feldspar, and most contain xenoliths of coarse-grained granite similar to that shown in figure 21. Dike 62-ASn-59 is a gray lamprophyre dike from Brooks Mountain, and it

contains rounded and resorbed xenocrysts of orthoclase up to an inch in length, obviously derived from the granite of Brooks Mountain, the only one in the area with phenocrysts of orthoclase that large.

Samples 64-ASn-410 and 62-ASn-786 are, respectively, from the lamprophyre plug near the Bessie and Maple prospects in Lost River valley, and from a thick lamprophyre near the pumphouse at the south end of the airfield at Lost River (figure 39, in pocket). The limestone around dike 62-ASn-786 is marmarized and cut by numerous veinlets of tactite and fluorite-beryllium rock, and granite must underlie the area within a few hundred feet.

Sample 62-ASn-RR11 represents one-half of the xenolith shown in figure 21. The granite of the xenolith is considerably more potassic than the granites of the exposed stocks, and the application of cobaltinitrite stain to the specimen shown in figure 21 proves that in the surrounding lamprophyre, the potassium content is enriched near the xenolith.

The remaining analyses shown on figure 22 represent the biotite granite stocks, with the exception of 64-ASn-RR24, which is a medium-grained granite dike near the northeast margin of the granite at Black Mountain (figure 2).

In table 3 (in pocket), the norms and main minerals of the modes of all the analyzed rocks are shown, as is the distribution of potassium feldspar as shown by staining.

In figures 23 to 27, textures of several lamprophyres are shown by photomicrographs, and in table 3 are shown the essential mineralogic compositions of the analyzed dikes, and their classification into the main types of lamprophyre, as listed broadly by Métais and

Figure 23. Typical dark lamprophyre dike without xenocrysts, showing augite phenocrysts (high relief) in a pilotaxitic groundmass of plagioclase laths, green to brown biotite, and opaque iron ores. Plain light. Magnification about 13.5 X. Specimen number 62-ASn-755.

STANDARD LIBRARY
UNIVERSITY OF MICHIGAN

Figure 24. Composite lamprophyre dike, medium-grained facies, showing xenocrysts of quartz (Q), and sericitized orthoclase (SO), in groundmass of orthoclase, albite, and minor biotite. Crossed nicols. Magnification about 13 X. Specimen number 61-ASn-407.

STANDARD LIBRARY
UNIVERSITY OF MICHIGAN

Figure 24a. Composite lamprophyre dike, fine-grained facies, showing large xenocrysts of oligoclase (Ol), orthoclase (Or), and quartz (clear, white), in fine-grained groundmass of plagioclase and green to brown biotite. Note recrystallized limestone fragment (C). Crossed nicols. Magnification 15 X. Specimen number 61-ASn-407A.

Figure 25. Typical dark lamprophyre dike that cuts composite dike shown in figures 24 and 24a, showing greatly resorbed xenocrysts of oligoclase (twinned), oligoclase partly replaced by orthoclase (O), and quartz (Q), in fine-grained groundmass of plagioclase, green to reddish-brown biotite, minor pyrite, and opaque iron ores. Crossed nicols. Magnification about 16 X. Specimen number 61-ASn-407B.

Figure 26. Lamprophyre dike from area of beryllium deposits on Rapid River, showing xenocrysts of plagioclase (twinned), quartz (clear), and orthoclase (black), in groundmass of plagioclase, green to brown biotite, carbonate and opaque iron ores. Crossed nicols. Magnification about 13.5 X. Specimen number 62-ASn-RR6. See table 3 for chemical analysis.

On the 11th, 12th, 13th, 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 24th, 25th, 26th, 27th, 28th, 29th, 30th, and 31st, the chemical and physical composition of the water was determined. The results are given in the following table:

Figure 27. Hornblende lamprophyre from dike near the granite in Tin Creek, showing large quartz xenocryst (Q) surrounded by hornblende, and large crystals of sphene (high relief), in a groundmass of plagioclase, brown biotite, fibrous green amphibole, and opaque iron ores. Plain light. Magnification about 18 X. Specimen number 62-ASn-TC23. See table 3 for chemical analysis.

Chayes (1963). In table 11 (in pocket), the trace element composition is shown, for these trace elements show conclusively that the lamprophyres cannot be late-stage differentiates of the granites.

Origin.--In figures 22, 28, and 29, the chemical and mineralogic composition of the rocks is plotted to demonstrate that the lamprophyres originated by granitic contamination of a nonalkalic mafic magma.

Figure 22 is a diagram showing oxide variations from the most mafic rock known in the York Mountains (62-ASn-266, the extrusive flow) through the most mafic lamprophyre (41-AC-66) into the granitic xenoliths and the granites. This diagram is based upon the analyses shown in tables 2 and 3; in each case the CO_2 has been calculated as calcite and omitted, along with water, with the remainder recalculated to 100 percent. The justification for this is that all the dikes analysed are intruded into limestones, and some are known to be contaminated by limestone. The recalculation attempts to minimize the effect of contamination. As is evident from the slopes of the lines, the more closely spaced the analyses are (in silica content), the greater is the disruption of the oxide lines; however, the general slopes remain rather similar. One dike (62-ASn-TC23) is noticeably different from the other lamprophyres in its high soda content, which is reflected in the development of blue-green hornblende which has replaced the pyroxenes. This is the only lamprophyre dike in which hornblende is noticeable.

In figures 28 and 29, the analyses are plotted in terms of normative minerals recalculated to 100 percent. On these diagrams, a point plotted below the anorthite-albite line indicates that the rock is silica-deficient. All three diagrams show a reasonably lineal trend from the most mafic rocks to the granites, and this trend is significant.

In tables 3, 4, 10, and 11, the trace elements of the various igneous rocks are compared. These elements show rather conclusively that the lamprophyres are not late-stage differentiates of the granites; in fact, it is difficult to consider them genetically related at all. It has long been firmly established that certain elements, particularly beryllium and lithium, are progressively concentrated during differentiation (for summaries, see Warner, et al, 1959, p. 20-25, and Shaw and Bernold, 1964, p. B100-B103). Seus (1962, p. 27) points out that the dark minerals of granites and late-stage alkalic rocks are always enriched in beryllium owing to the large number of diadochic substitutions possible in these complex minerals. Because the lamprophyres here discussed contain a high percentage of biotite and pyroxenes, capable of accepting large amounts of beryllium, the writer reasons that if the lamprophyres were late-stage differentiates of the granites, that they would be enriched in beryllium as well as in boron, lithium, and tin, which is not the case. The granites discussed here are abnormally rich in beryllium, boron, lithium and tin (table 10).

When considered in conjunction with the chemical disequilibrium of the lamprophyres, and their large content of granitic xenoliths and xenocrysts obviously derived from coarse-grained granite, the dearth of tin, beryllium, and other rare elements in the lamprophyres indicates that they originated by granitic contamination of mafic rocks that are low in silica and rare elements.

Throughout the central York Mountains, the most striking association of the lamprophyres is not the association with granites, but with a strong set of normal faults striking N. 60°-85° E., and which locally cut

the exposed granite stocks. Lamprophyre dikes near and in the granite of Tin Creek have chilled borders, proving that the wall rocks were cool when the dikes were intruded. The aggregate downthrow on the normal faults is in thousands of feet, which suggests that a considerable time elapsed between intrusion of granite and intrusion of lamprophyre. Within the lamprophyres, the presence of both xenoliths up to several inches in diameter, as well as corroded individual xenocrysts, suggest that the dikes injected solid granite and possibly granite "mush", which allowed the individual crystals to separate easily.

Chemically, the lamprophyres contain rather low silica, relatively high K_2O and Na_2O , a high content of TiO_2 and total iron, a dearth of light elements except in dikes containing xenoliths of granite, and a relatively high content of copper, nickel and chromium, the latter a feature characteristic of mafic rocks. The chemical composition suggests mixing of two magma types, mafic and granitic, as does the trace elements, but physical relations suggest that a considerable time elapsed between intrusion and cooling of the exposed stock, and injection of lamprophyres. Following injection of the lamprophyres, large ore bodies of tin, tungsten, beryllium and fluorine were formed, guided in large part by lines of weakness intruded by dikes of lamprophyre, as well as older rhyolite, which proves that the lamprophyre dikes, although not themselves carrying these rare elements, probably penetrated igneous rocks at depth which did contain these elements in a heated environment, which could furnish elements to form ore deposits of rare and light metals.

All of the features outlined above would follow naturally if deep-seated mafic magma were tapped by normal faults which also cut

granite that was emplaced earlier, and that had cooled in its upper parts. The physical and chemical features of the lamprophyres cannot possibly have originated by any known process of differentiation from a single parent magma.

It is concluded that the association of lamprophyres with granite in the central York Mountains is really a tectonic association rather than a genetic one. It seems probable to the writer that generation of granitic magma in the crust in a tectonic belt would weaken the crust by forming a liquid melt in the crustal rocks. Mafic magma from the sima would tend to rise into the tectonic belt along all lines of weakness, which would include the margins of granites which were cooling from the top down. In their lower, hotter parts, the ore elements and volatiles characteristic of the granites and the ore deposits of the central York Mountains, namely beryllium, tin, tungsten, boron, fluorine and lithium, would be trapped. If normal faults fractured the cooled parts of the granites, and penetrated through hotter parts of the granites to depths where basalt from the sima was available, mafic magma would rise into the faults. Locally it would penetrate through hot granite, which, though still retaining trapped volatiles and rare elements, would be essentially solidified and capable of fracturing. Such dikes would acquire silica, potassium and sodium from the granites, but not in sufficient quantity to completely mask their mafic origin. In their upper parts, the dikes would cool rapidly in the cool rocks into which they were injected, and locally, hydrothermal fluids from the lower parts of the granite would rise along some of the dikes as well as into some fractures not invaded by mafic magma, and would form

tin and beryllium deposits similar to those of the central York Mountains, which must be genetically related to the granites. This is believed to be what happened in the western Seward Peninsula.

After preparation of this report, and submission of it in preliminary form to Stanford University as a PhD thesis, Dr. Adolph Knopf and I discussed the lamprophyres. At this time, he referred me to a paper in German which also concludes that lamprophyres and granites in Germany are a tectonic association rather than a genetic one (Chatterjee, 1959, p. 1-24), and the interested reader is referred to this paper for an excellent discussion of the problem. In the central York Mountains, the fortuitous association of lamprophyre with rocks and ores containing tin and beryllium presented an unusual opportunity for the writer to reach a similar conclusion by investigating these trace elements, and to give support to the ideas expressed by Chatterjee.

Age

The age assigned to the igneous rocks is based upon a single age determination by Marvin Lanphere, U.S. Geological Survey, who, by use of the potassium-argon method, dated pure biotite separated by the writer from the granite of Brooks Mountain as Late Cretaceous (personal communication, 1962). As the lamprophyre dikes post-date the consolidation and fracturing of the granites by an unknown time, they may be as young as early Tertiary in age. For the present, however, it is best to call them Late Cretaceous for the most part, and they are so shown on the geologic maps, but the possibility exists that they may in part be of Tertiary age.

ORE DEPOSITS

Tin

Economic Importance

Placer deposits of tin have been known in the mapped area since 1900 (Brooks, 1901). By 1954, some 2,200 tons of tin metal had been produced from the Seward Peninsula, and production from placer deposits at Potato Mountain continued until 1960. Commercial production from the main lode deposit at Lost River was limited to the periods 1913-1914, when 3.5 tons of tin and .6 ton of tungsten was produced, and the period 1949-1955, when 83.4 tons of tin were produced from placer deposits, and 342.2 tons of tin were produced from lode deposits (U.S. Bureau of Mines). Geologic mapping of the mine, combined with assay data of the Lost River Tin Corporation, enabled computation of ore reserves and resources of the mine area. These are summarized in table 4, following.

Several other tin prospects are known in the map area. Most are presumed to be smaller or of lower grade than the deposits at Lost River mine, but in the aggregate they may contain considerable tin. In 1965, U.S. Steel Corporation optioned the Lost River mine, as well as other claims in the area, and are planning to evaluate the deposits as a potential large tonnage open-pit (oral communication, S. G. Sargis). Depending upon the cut-off grade selected, and the by-product recovery of copper, lead, zinc, tungsten, molybdenum, beryllium and fluorite, the tonnages available for open-pit evaluation exceed by probably ten times the figures quoted in table 4.

Although the amount of tin totalled in table 4 (23,000 tons) is only about 50 percent of U.S. requirements of primary tin for the single year 1963 (U.S. Bureau of Mines, Minerals Yearbook, 1963), it

Table 4. Tin and tungsten reserves of the Lost River mine^{1/}

Measured and Indicated Reserves				
<u>Tin ore only</u>				
Tons ore	Average percent of Sn	Average percent of WO ₃	Total tin, lbs.	Total WO ₃ (Units)
200,500	1.3	0.125 ^{2/}	5,200,000	
<u>Mixed tin-tungsten ore</u>				
105,000	.76	.60	1,600,000	62,500
			6,800,000	62,500
Total tin and WO ₃				
Inferred Reserves				
80,000	1.5	N.E. ^{3/}	2,400,000	
430,000	1.0 ±	N.E.	8,600,000	
Total			11,000,000	
Potential Resources				
650,000	.40	N.E.	5,200,000	
840,000	.26	N.E.	4,368,000	
3,000,000	.30	N.E.	18,000,000	
Large	lower grade	N.E.		
Total			27,568,000	
Grand totals		greater than	45,368,000	62,500

^{1/} After Sainsbury, 1964, p. 50-55.

^{2/} Probably not recoverable at such low concentration.

^{3/} Not estimated.

LANCASTER BOND

100% COTTON FIBRE

U.S.A.

represents by far the largest lode reserve of tin of comparable grade known in the United States. Continued exploration of deposits known in the map area, and of deposits yet to be found, based upon the areal distribution of tin and beryllium deposits, may be expected to enhance the national importance of the tin area.

Geology

For the most part, the tin deposits consist of the minerals cassiterite and stannite associated with numerous sulfide minerals and fluorine or boron-bearing gangue minerals. The deposits are localized along dikes intruded into faults of the N. 60°-85° E. system, in numerous small veins and veinlets in limestone above granite cupolas, and in parts of granite stocks that contain fluorine-bearing minerals. All known deposits are associated with biotite granite, or dikes that presumably lie above granite. For detailed descriptions, the reader is referred to Knopf (1908) and Sainsbury (1964).

In the present study, investigation of the mineralogy of the lode tin deposits was limited to X-ray identification of minerals that form sulfide assemblages in the central zones of tabular beryllium-fluorite veins. The cores studied came from holes drilled by the U.S. Bureau of Mines in the newly discovered beryllium-fluorite deposits in Camp Creek (figure 31) and near the Bessie-Maple tin prospect in Lost River Valley, the geology of which is shown in figure 39. Drilling by the U.S. Bureau of Mines in 1964 gave valuable information on the relations between the tin and beryllium, as discussed below.

Diamond-drill hole 115, in the upper plate of the Rapid River fault (figure 39), penetrates broken dolomite intruded by lamprophyre dikes. With minor variations, the hole penetrates 17 feet of broken

dolomite, 16 feet of fluorite with chrysoberyl and diaspore, 1 foot of essentially solid sulfide minerals that include stannite, pyrite, sphalerite, arsenopyrite and galena, then dolomite and fluorite that contains sulfides, and that lies along the walls of a lamprophyre dike, then fluorite-beryllium rock, and finally dolomite. In several other holes in Camp Creek and at the Bessie-Maple area, beryllium-fluorite deposits have a central core of sulfide minerals similar to those in drill hole 115, and this information has proved valuable in support of the concept of the zonal distribution of the tin and beryllium deposits, as developed later in this paper.

Beryllium Deposits

Economic Importance

Large replacement deposits of beryllium and fluorite of a type found previously only in Russia (Govorov, 1958) were found as a result of the field studies that form the basis of this report. By late 1964, exploration had shown that these beryllium deposits contained at least 4,500 tons of beryllium metal in material containing more than .2 percent BeO (Sainsbury, 1964). This amount of beryllium is some 12 times the total known U.S. reserves in pegmatites of comparable grade. In conjunction with the discovery of non-pegmatite deposits of beryllium in Utah (Staatz and Griffitts, 1962), the Alaskan deposits showed decisively that the world's resources of beryllium are not in pegmatites, as supposed as recently as 1960 (U.S. Bureau of Mines, Bull. 585, p. 97), but are non-pegmatite. Adequate domestic deposits of ore, in bodies of such size and continuity that ore reserves sufficient to allow sustained mining may be established by grade and tonnage by

diamond drilling, has freed the U.S. beryllium industry from dependence upon foreign sources of beryl, although at present (1965), beryl still furnishes most of the beryllium used by industry.

General Description

The beryllium lodes described herein consist of replacement veins and veinlets in limestone or dolomite, with fluorite as the major mineral in the ores, amounting to an average of about 50 percent. In bulk samples of ore, a rough correlation exists between fluorine and beryllium, the ratio F:Be approximating 115:1 in several samples, although the ratio varies from 58 to 251, as shown in table 5. Trace element content of typical ores is shown in table 5a. Typically, the fluorite-beryllium ores display a faint to marked banding on a scale of 1-2 mm, the bands being caused by an imperfect rhythmic layering of fluorite, and fluorite intergrown with diaspore, mica, tourmaline and chrysoberyl. The layering probably represents replacement "fronts." In some specimens, the original argillaceous bands in the limestone are perfectly preserved (figure 30), and all data suggest that replacement was volume for volume. A photomicrograph of typical ore is shown in figure 31. In most ores, both chrysoberyl and diaspore form thin cross-cutting cryptocrystalline veinlets that are opaque in transmitted light and ^{curdy}crudy-white in reflected light (figure 31). The diaspore in these veinlets contains up to 2.5 percent BeO, probably in the diaspore lattice, as X-ray patterns reveal no sign of a discrete beryllium mineral to account for the high beryllium content. At the extreme ends of replacement lodes, the diaspore is almost barren of beryllium. From place to place in the ores, mineralogical variations

Table 5. Ratio of fluorite to beryllium in ores^{1/}

Analysts: Fluorine, Ardith Bartel; beryllium, L. F. Rader,
U.S. Geological Survey

Sample No.	Location	Be Percent	F Percent	F/Be
303147	Rapid River	0.24	27.6	115.0
303148	Rapid River	0.24	27.5	114.6
303149	Bessie-Maple	0.14	28.6	204.3
303150	East Lost River	0.25	24.4	97.6
303151	East Lost River	0.15	23.0	153.3
303152	East Lost River	0.17	27.1	159.4
303153	Camp Creek, west	0.25	28.9	115.6
303154	Camp Creek, west	0.11	27.6	250.9
303155	Camp Creek, west	0.20	29.5	147.5
303156	Camp Creek, west	0.24	27.7	115.4
303157	Camp Creek, center	0.26	28.4	109.2
303158	Camp Creek, center	0.26	29.0	111.5
303159	Camp Creek, east	0.54	31.2	57.8
303160	Camp Creek, extreme east	0.23	27.3	118.7

Spectrographic analyses of these ores are shown in table 5a.

Mineralogically, the usual ore consists of the following minerals, in volume percent: fluorite 45-65; diaspore 5-15; tourmaline 0-10; white mica 0-5; chrysoberyl 3-10; and minor amounts of other minerals, notably hematite and todorokite (a manganese mineral). Owing to the high content of fluorite, the beryllium ores are noticeably heavy, ranging from 2.95 to 3.45 in specific gravity.

^{1/} Bulk chip samples from float.

Figure 30. Cryptocrystalline veinlet of curdy-white chrysoberyl and diaspore cutting fluorite-beryllium rock. Dark vertical bands are relict argillaceous layers(A). Light, wavy, horizontal bands are diaspore-chrysoberyl veinlets(V). Note that the argillaceous bands are not displaced by the ore veinlets. Volume for volume replacement is suggested. True size.

lower, basal mass. In lower, fluorite is black, light patches are mica, tourmaline and diaspore with chrysoberyl. Magnification about 15 x.

Figure 31. Cryptocrystalline veinlet of curdy-white chrysoberyl and diaspore cutting fluorite-beryllium rock. Upper, oblique light, lower, crossed nicols. In lower, fluorite is black, light patches are mica, tourmaline and diaspore with chrysoberyl. Magnification about 15 X.

occur - for instance, a heavy-liquid separation from one specimen will contain both chrysoberyl and diaspore, whereas separations from other specimens in the same area may contain only chrysoberyl alone. These variations have not been investigated in detail.

In all the ores, the mica is muscovite type, but it contains some beryllium and lithium, and is here referred to as "white mica".

Beryllium Minerals and Paragenetic Sequence

Five distinct beryllium minerals have been identified in the ores. These are chrysoberyl (Al_2BeO_4), euclase $[\text{AlBeSiO}_4(\text{OH})]$, beryl ($\text{Al}_2\text{Be}_3\text{Si}_6\text{O}_{18}$), bertrandite $[\text{Be}_4\text{Si}_2\text{O}_7(\text{OH})_2]$ and helvite $[(\text{Fe}, \text{Mn}, \text{Zn})_4\text{Be}_3\text{Si}_3\text{O}_{12} \cdot 5]$. In addition, bityite $[(\text{Ca}, \text{Na}, \text{K})(\text{Al}, \text{Li}, \text{Mg})_{2-3}(\text{Si}, \text{Al}, \text{Be})_4\text{O}_{10}(\text{OH})_2]$ and phenakite (Be_2SiO_4), are identified provisionally, but have not yet been confirmed by X-ray patterns. The bityite was identified by the U.S. Bureau of Mines (R. V. Berryhill, oral communication, 1964). In a preliminary report (Sainsbury, 1963) milarite(?) was identified, but new work casts doubts on this determination, which was based upon the optics of a few minute grains in fluorite. It is more probable that this mineral is an unidentified fluoride.

In table 6 are indexed the X-ray data of the chrysoberyl, euclase, bertrandite, diaspore, and todorokite separated from ores. Helvite was identified by optics and staining (Gruner, 1944), and beryl was identified by crystal form and X-ray pattern, although its pattern is not indexed in table 6. A copy of the diffractometer tracings of those minerals so identified is included in the appendix (in pocket).

The first beryllium mineral to form was helvite, which occurs only in banded skarn (skarn, as used herein, is a tectite containing abundant magnetite) consisting of bands of fluorite and magnetite (figure 32). Jahns (1944b, p. 79) was the first to identify beryllium in a sample of this rock, which is similar to the helvite-bearing skarn that he called "ribbon rock", at Iron Mountain, New Mexico (Jahns, 1944b). In the Lost River area, the helvite-bearing skarn is within a few feet of the contact of granite and limestone in Tin Creek, and is not economically significant. It has been described in detail by Knopf (1908, p. 45-49). Whereas the helvite in the Iron Mountain skarns is restricted to the fluorite bands, it is much more common in the magnetite bands in the Tin Creek rocks. The helvite forms small grains as much as 2 mm in diameter, and locally is so abundant as to account for 0.45 percent BeO in a specimen. The banded fluorite-magnetite rock locally is surrounded by tectite formed of hornblende, garnet, vesuvianite, fluorite, and minor other minerals, and both tectite and banded skarn locally are cut by younger fluorite-beryllium veinlets containing chrysoberyl.

By far the most common beryllium mineral is chrysoberyl, which is the second beryllium mineral in the paragenesis. Pure chrysoberyl has been separated from many specimens of the banded fluorite ores; a typical separation is shown in figure 33. A semiquantitative spectrographic analysis of a purified separate showed that it contained 19.8 percent BeO, the theoretical maximum for chrysoberyl. In this section, the chrysoberyl is seen to occur as discrete anhedral grains up to a few millimeters in diameter, as cryptocrystalline veinlets up to several millimeters across (figure 34), and in minute grains a few microns in diameter intergrown with fluorite, mica, and diaspor.

Figure 32. Rhythmically banded skarn ("ribbon rock") from the contact of the granite in Tin Creek. Light bands are fluorite, dark bands are magnetite. Helvite occurs in isolated grains principally in the magnetite bands. True scale.

Figure 33. Chrysoberyl separated from fluorite-beryllium ore from Rapid River. Crossed nicols. Magnification about 13 X. Separated from specimen 61-ASn-413, shown in figure 34.

3. Transmitted light, crossed nicols
 Figure 34. Portion of specimen fluorite-beryllium ore, Rapid River, Alaska. Upper shows chrysoberyl (light), lower shows same in transmitted light (black). Fine-grain intergrowths scatter transmitted light, giving darkness. Gray areas are fluorite, light areas are zircon, tourmaline, diaspore and minor chrysoberyl. Specimen number 61-ASn-413.

A. Oblique plain light

B. Transmitted light, crossed nicols

Figure 34. Texture of typical fluorite-beryllium ore, Rapid River, Alaska. Upper shows curdlike chrysoberyl (light), lower shows same in transmitted light (black). Fine-grain intergrowths scatter transmitted light, giving darkness. Gray areas are fluorite, light areas are mica, tourmaline, diaspore and minor chrysoberyl. Specimen number 61-ASn-413.

In veins in Camp Creek, nodules up to a foot in diameter are common. These nodules (figure 34b) consist of round to subround masses of intergrown diaspore and chrysoberyl surrounded by a zone in which fluorite, mica, and todorokite are the commonest minerals, and finally by a rind of faintly purple-colored fluorite with some mica and todorokite. These nodules represent a great enrichment of beryllium compared to the surrounding ores, and somewhat resemble the nodules in the non-pegmatitic beryllium deposits at Spor Mountain, Utah (Staatz, M. H., and Griffiths, W. R., 1961, p. 946-947).

The beryllium mineral euclase is the third beryllium mineral in the paragenesis. It is known in ores at Rapid River and Tin Creek. At Rapid River, it is confined to veinlets that cut the banded ores and that consist of fluorite, mica, and euclase. In these veinlets, which usually do not exceed an inch or so in thickness, the euclase forms lustrous pearly-white flakes as much as a centimeter long. It is especially common in specimens from Tin Creek, where it is confined to veinlets of mica and fluorite that cut the banded ores, or to unusual tabular growths on banded ore (figure 35). In the specimen shown in figure 35, the tabular growths consist of an intimate intergrowth of fluorite and mica, with the mica oriented with the 001 face perpendicular to the major plane of the growth. From crushed tabular growths, euclase can be separated by gravity methods. In the banded ore which is coated by these unusual growths, only chrysoberyl can be recovered.

Figure 34b. Cross section of a nodule from the Camp Creek deposits.

Light, concentrically banded areas (C) consist of chrysoberyl with diaspore and minor white mica, which are surrounded by colorless fluorite containing mica, diaspore, chrysoberyl, and todorokite (M). Rim and center are cemented by pale-purple fluorite (F) with minor mica and todorokite (black specks).

bertrandite is unaltered paragenetically with respect to euclase, but it is confined to veinlets that cut the banded chrysoberyl-bearing zone, and hence is younger than chrysoberyl. It has been recovered in minute amounts, not sufficient to give a good powder.

Figure 35. Beryllium-fluorite ore from veinlets in marble on the south side of the granite in Tin Creek. Tabular growths consist of fluorite with white mica oriented transverse to the flat surfaces, and minor euclase. Growths coat usual fluorite-beryllium rock (dark) which contains chrysoberyl, mica, tourmaline, and diaspore. Specimen 62-ASn-TCh3.

found crosscutting the euclase veinlets.

Bertrandite is unclear paragenetically with respect to euclase, but it is confined to veinlets that cut the banded chrysoberyl-bearing ores, and hence is younger than chrysoberyl. It has been recovered in minute amounts (yet sufficient to give a good powder pattern as a smear on a glass slide) from veinlets of fluorite, mica and euclase on Rapid River. It has not been identified in thin section.

In a few thin veinlets cutting a specimen of banded ore from Rapid River, associated with minor quartz, phenakite(?) has been identified optically. It forms small crystals some .05 mm in diameter, intergrown with quartz and mica. Its identification is based upon the following optical constants: Uniaxial +, sign of elongation -, indices estimated to be between 1.65-1.67, and upon the fact that the veinlets contain an enrichment of beryllium readily detectable with the beryllium analyzer. Phenakite has been reported also from drill cores from the Lost River mine (Heide, 1946, p. 25), and a few minute grains were recovered from drill cuttings from altered granite at the Lost River mine. With regard to its position in the paragenetic sequence of beryllium minerals, it can only be said that phenakite is younger than chrysoberyl, and probably younger than euclase and bertrandite, for it is associated with quartz, a mineral totally lacking in the banded ores containing chrysoberyl, and in the veinlets that contain euclase and bertrandite. The veinlets containing phenakite(?) have not been found crosscutting the euclase veinlets.

Beryl probably is the last primary mineral to crystallize in the sequence. To date, beryl has been found only in a single quartz-mica-fluorite vein some 4-6 inches thick on the surface at the Lost River mine, between the Cassiterite and Ida Bell dikes east of Cassiterite Creek (figure 37). At two places in this vein, perfect crystals of beryl some 1/4 inch across and 1/2 inch long occur in vugs. Some are coated with an earthy brown material about 2 mm thick, which was determined by X-ray to be muscovite stained by iron. In the immediate mine area, quartz veins have been observed crosscutting numerous small fluorite-chrysoberyl veinlets, free of quartz, that ramify through the limestone, and hence beryl can be assumed to be younger than chrysoberyl, and probably younger than bertrandite and euclase.

Mineral Assemblages.---In table 7 are tabulated the mineral assemblages in which the beryllium minerals occur.

Table 7. Mineral assemblages in beryllium ores

Beryllium mineral	Associated minerals
Helvite	Magnetite, fluorite, amphibole, minor minerals
Chrysoberyl	Fluorite, diaspore, white mica, tourmaline, hematite, todorokite (locally stannite, arsenopyrite, sphalerite, galena)
Euclase	Fluorite, white mica, bertrandite(?)
Bertrandite	Fluorite, white mica, euclase(?)
Phenakite	Fluorite, quartz, muscovite mica
Beryl	Quartz, fluorite, muscovite mica

In the above mineral assemblages, it is noteworthy that fluorite always accompanies the beryllium minerals. Certain deductions can be made from the assemblages regarding the composition of the solutions responsible for the paragenetic succession of minerals. At first, alumina must have been high, and the formation of kaolinite from diaspore probably was prevented either by a high temperature (unlikely), or a low $(H^+)/(K^+)$ ratio. With progressive crystallization, silica increased in amount (or activity), and water became more abundant, as evidenced by the appearance of hydrated beryllium minerals. By the time hydrated beryllium minerals appeared, alumina had decreased either in amount or activity to such a degree that the highly aluminous minerals chrysoberyl and diaspore no longer formed.

At Tin Creek, as elsewhere, the beryllium mineral helvite represents a special case. Its restricted formation can be explained in terms of sulfur pressures, and the necessity for numerous other cations, notably iron, manganese, and zinc, to be available during its formation. The sulfur pressure (or activity) was below that necessary to convert magnetite to pyrite or pyrrhotite, but was sufficient to readily furnish sulfur to form helvite, and minor other unidentified sulfides. Elsewhere where helvite has been found, it occurs in manganese veins, as at Butte (Hewett, 1937); in skarns, as at Iron Mountain, New Mexico (Jahns, 1944, p. 56) or in sulfide-bearing deposits that have skarn associated, as at Beaver, Utah (Sainsbury, 1963, p. 395-396). In all these localities, the deposits commonly include minerals of copper, lead, and zinc, as well as manganese-bearing garnets.

Chemical Changes in the Formation of the Beryllium Lodes

The difficulties inherent in the quantitative analyses of materials that contain a high percentage of fluorine render chemical analyses of such materials expensive, and subject to considerable error. Under the able direction of Lee C. Peck, Ellen S. Daniels made an analysis of a bulk sample of beryllium-fluorite ore from Rapid River. This ore had replaced an argillaceous limestone, which was analyzed by Christel L. Parker. Although it proved impossible to achieve analysis that totalled 99.00 percent, the analysis of the ore is presented in table 8, where the chemical composition is compared to that of the argillaceous limestone, and the gains and losses in grams per 100 cc. of rock are shown. As illustrated by figure 30, the replacement of limestone by fluorite-beryllium rock was probably volume for volume, and the gains and losses can be compared with considerable confidence.

As shown by the table, the main chemical changes during the formation of a typical ore from argillaceous limestone involved the addition of fluorine, alumina, silica, water and alkalies to the limestone, and the loss of carbon dioxide. The oxide of calcium remained surprisingly constant, which reflects the fixation of calcium in the mineral fluorite. In a previous publication, Sainsbury (1960, p. 1491-1495) showed that during the formation of the tin lodes in greisen at the Lost River mine, alumina and fluorine increased, and that during greisenization silica initially increased and then decreased sharply. During greisenization of granite, K_2O and Na_2O were lost to the ore solutions. If the

TABLE 8.—*Chemical changes during conversion of limestone to fluorite-beryllium ore*

[Analysts: Christel L. Parker, limestone; Ellen S. Daniels, ore, U.S. Geol. Survey]

Lab No.	D100123		D100397			
Field No.	62-ASn-RR23		62-ASn-RR1			
Sample type	Bulk chip, argillaceous limestone		Bulk chip, ore			
Specific gravity	2.70		3.25			
	Weight percent	Grams per 100 cc	Weight percent	Recalculated to 100 percent	Grams per 100 cc	Change, grams per 100 cc
SiO ₂	7.35	19.85	14.64	15.18	49.34	+29.49
Al ₂ O ₃	2.15	5.81	18.55	19.24	62.53	+56.72
Fe ₂ O ₃	.39	1.05	.70	.73	2.37	+1.32
FeO	.58	1.57	.22	.23	.75	— .82
MgO	2.03	5.48	1.60	1.66	5.39	— .09
CaO	47.67	128.71	40.02	41.50	134.87	+6.16
Na ₂ O	.05	.14	1.35	1.40	4.55	+4.41
K ₂ O	.42	1.13	1.21	1.25	4.06	+2.93
H ₂ O ⁺	.51	1.38	2.07	2.15	6.99	+5.61
H ₂ O [—]	.09	.24	.12	.12	.39	+ .15
TiO ₂	.10	.27	.06	.06	.19	— .08
P ₂ O ₅	.03	.08	.01	.01	.03	— .05
MnO	.02	.05	.14	.14	.46	+ .41
CO ₂	38.30	103.41	.16	.17	.55	—102.86
Cl	.01	.03	.00	.00	.00	— .03
F	.05	.14	27.00	27.99	90.97	+90.83
Subtotal	99.75	269.34	107.86	111.83	363.44	+198.03
Less O=F ₂	.02	.05	11.37	11.79	38.31	—142.27
Total	99.73	269.29	96.49	100.04	325.13	¹ 55.76
					—269.29	
Difference					55.84	

¹ Unaccounted for, 0.08.

proposed zonal distribution of the beryllium lodes outward from tin lodes, as shown in figure 42, is valid, the transport of elements should be reflected in the beryllium lodes. The observed trends are compatible with respect to silica, fluorine, and the alkalis, for these materials were abstracted from the granites during greisenization and were added to the beryllium lodes. Alumina was added in large amount during greisenization and during the formation of the beryllium lodes. The source of this alumina must have been the feldspars of a deep granite mass, and the aluminum was probably transported as a fluoride complex, for the ion $[AlF_6]^{-3}$ is stable in water (Fiegl, 1929). As the ion $[BeF_4]^{-2}$ is stable, as is the ion $[SiF_6]^{-2}$, it is most probable that the elements Si, Al and Be were transported in the ore-forming fluids as stable fluoride complexes. Reaction between the fluorine in ore-forming fluids and limestone wallrocks would remove fluorine from the solutions, leading to the eventual breakdown of the fluoride complexes and the deposition of aluminum, beryllium, and silicon, as indicated by the chemical analyses.

Main Deposits

Within the central York Mountains, beryllium deposits of economic significance were found by the Geological Survey in five main areas, all of which lie within a belt a few miles wide trending about N. 85° E. across the drainage basin of Lost River, parallel to the main dike swarm (figure 2). With the possible exception of the small veins around the granite in Tin Creek, all the deposits occur where lamprophyre dikes intrude shattered limestone or dolomite

beneath the Rapid River fault. In each area, ore forms veins traceable for several hundred feet, smaller veins and veinlets that cut the shattered carbonate rocks locally forming stockworks or pipelike bodies, and narrow replacement veins along joints. In most areas, ore has formed along the walls of some of the lamprophyre dikes. Exploration has shown that ore widths range from a fraction of an inch to as much as 18-20 feet, and that in four of the areas mineralization is essentially continuous for several thousand feet along the Rapid River fault. Hence, one result of the investigation was to establish the Rapid River fault as a major ore-bearing structure, the first such structure known on the Seward Peninsula.

In order to develop the concept of a zonal relation between the tin and beryllium deposits, brief descriptions of each main beryllium area are in order. The deposits are described by area from west to east, as follows: Rapid River, Curve Creek, Lost River valley (Bessie-Maple), Tin Creek, Camp Creek, Lost River mine (see figure 2).

Rapid River.--The deposits on Rapid River were discovered on public domain by the writer in 1961, and were explored by Newmont Mining Company in 1963, after detailed geologic maps were prepared by the U.S. Geological Survey in 1962. The geology of the area of beryllium deposits is shown on figures 37 and 38 (in pocket). The deposits consist of veins, veinlets, and pipes of veined limestone and dolomite that consist of the usual banded fluorite-beryllium rock, and that are aligned along the Rapid River fault for about 4,400 feet. The best deposits lie east of Rapid River on a wide

bench covered thinly by tundra and frost-riven bedrock, over an area some 800 feet long and 300 feet wide. Beneath the Rapid River fault, the bedrock consists principally of thin-bedded argillaceous limestone of Early Ordovician age, whereas the rocks of the upper plate are medium- to thick-bedded gray limestone of later Early Ordovician age. Beneath the Rapid River fault, the beds are intricately folded and broken, and drilling by Newmont Mining Company suggests that a lower thrust some 200-300 feet vertically beneath the Rapid River fault has been important in localizing the richer ore, which forms a tabular zone dipping about 20° south. The lower thrust has not been identified on the surface. A swarm of lamprophyre dikes cuts through the mineralized area into the upper plate of the Rapid River fault. Most of the dikes strike about N. 80° - 85° E., and most are bordered by brecciated and dolomitized limestone, locally converted to taektite. Some zones of richer fluorite-beryllium rock up to 18-25 feet wide are localized along fractures that in parts contain lenticular lamprophyre dikes (see inset, figure 37). At the west end of the better ore, where a small tributary enters Rapid River, bedrock is well exposed, and the geologic relations are shown in figure 38. Here, it is seen that the lamprophyre dikes are discontinuous and lenticular, and that for the most part the fluorite-beryllium veinlets formed by replacement of limestone along the walls of joints, the attitude of which is controlled in part by small-scale folds.

At the surface, the beryllium lodes contain only the minerals fluorite, diaspore, tourmaline, white mica, and chrysoberyl, with

specks of hematite, and minor other beryllium minerals, notably euclase, bertrandite, and phenakite(?). Drill core obtained by Newmont Mining Company from holes that intersected the beryllium ores several hundred feet below the surface contains noticeable sulfide minerals, including galena, sphalerite and minor cassiterite associated with the beryllium ore (Peter O. Sandvik, oral communication, 1963). Toward the east end, the beryllium-fluorite veins give way to fine-grained silica with specks of fluorite and only low beryllium. Hence, a vertical zonation at depth into sulfide minerals and a lateral zonation to fine-grained silica is a characteristic of the Rapid River deposits. The large number of dikes suggests also that a granite stock, or cupola, will be found at depth, which, however, will probably exceed 500 feet vertically. This figure is based upon the absence of contact effects in the overlying limestones.

Curve Creek.--The deposits on the south side of Curve Creek were discovered on public domain by the writer in 1964, largely as a result of geologic projection. The ores consist principally of silica, fluorite, and pyrite, locally with stibnite(?) and diaspore. The beryllium content is low to moderate. In these deposits, which lie within the shattered limestone beneath the Rapid River fault, the fluorite is colored purple to faint lilac, similar to that at the east end of the Cassiterite dike of the Lost River tin mine, several thousand feet from the tin ore shoot. Several dikes, partly altered, intrude the Rapid River fault, and are oriented N. 80°-85° E. along the regional fracture pattern. The ore occurs

discontinuously along the fault for about 4,000 feet, the richer parts being near the dikes. In the absence of subsurface exploration, the zonation at depth is unknown, but the mineralogy of the ores, the purple coloration of the fluorite, and the low beryllium content correspond to the outer zone of the ore shoot of the Lost River tin mine as observed in the north headwaters of Camp Creek. No geologic maps have yet been prepared of this deposit.

Lost River Valley.--These lodes were found by the writer and Thomas E. Smith in 1962, and are covered in part by claims staked in 1962 and 1964 by Lenhart Grothe and Thomas Pearson, owners of the Lost River mine, by Barbara Wenkley of Bondi, Australia, and by James Tozer. The deposits on the west end lie within ground covered by old patented mining claims, known as the Bessie-Maple claims, staked prior to 1906 on a prospect containing tin and sulfide minerals (Knopf, 1908, p. 57).

The deposits occur for some 5,000 feet along the Rapid River fault where it crosses the valley of Lost River. In this area, the fault dips south at a low angle. A detailed geologic map is shown in figure 39 (in pocket). The deposits have been explored on the east end by trenches of United States Smelting, Refining and Mining Co., and by three diamond-drill holes and two trenches of the U.S. Bureau of Mines on the west end. Throughout the mineralized zone, dark lamprophyre dikes, dipping steeply, pierce the Rapid River fault, as does a lamprophyre plug.

At the west end, near the Bessie-Maple prospect, both sulfide-tin deposits as well as the usual fluorite-beryllium deposits are found in complex relations; in the center part, only the fluorite-beryllium lodes are found; on the extreme east end (Toser prospect), the fluorite-beryllium lodes give way to the east to rusty float boulders of fine-grained silica. The relations observed at the surface and in drill cores (Sainsbury, 1965) show that at least part of the fluorite-beryllium rock lies on both walls of the sulfide veins. The sulfide assemblage, which includes stannite as a major tin-bearing mineral, and the high silver content of the sulfide ores is characteristic of that found elsewhere in the world where silver-bearing sulfide minerals form an envelope about cassiterite deposits, e.g., at the San Antonio mine, Mexico (Hewitt, 1943). West of Lost River, a float run of fine-grained silica with fluorite lies on the eastern end of the main beryllium deposits, repeating exactly the along-strike zonation to silica observed at Rapid River.

The fluorite-beryllium deposits consist principally of the usual mixture of fluorite, diaspore, tourmaline, white mica and chrysoberyl. Late veinlets of diaspore are rich in beryllium; the fluorite for the most part is colorless, although late fluorite is lilac colored. Irrespective of whether the ore has replaced limestone or dolomite, the mineral assemblages are the same. The wide zone of beryllium-fluorite rock on the walls of the main tin deposit at the Bessie-Maple contains ore of distinctly lower grade than the usual ores, a relation that is true also at the Lost River tin mine (see page 106 for discussion).

In Lost River valley, zonation from tin to beryllium is rapid in a direction perpendicular to the tin veins, and occurs within a few feet. Along the strike of the main beryllium veins, the zonation of sulfide minerals to fluorite-beryllium rock and thence to fine-grained silica with fluorite and locally with sulfide minerals is demonstrated, but requires hundreds to thousands of feet.

Tin Creek.--The beryllium deposits in Tin Creek were found by the Geological Survey in 1962. Most of the beryllium deposits are replacement veins and veinlets in marble on the south side of the granite, whereas tin deposits are found around the granite (figure 40, in pocket). Several trenches excavated by United States Smelting, Refining and Mining Company have exposed replacement veinlets of fluorite-beryllium rock up to several feet thick in marble, but most of the replacement veins are less than a foot thick. In places, the veinlets are especially common along fractures, some of which may be joints trending N. 70°-85° E. parallel to the dikes that have intruded the regional fracture system. At other places, replacement veinlets are concentrated at the margins of dikes which trend at high angles to the granite contact, giving the impression of a vein parallel to the dike. Mineralogically, the beryllium lodes are more diverse than elsewhere, for, although some are the usual mixture of fluorite, tourmaline, diaspore, white mica, and chrysoberyl, others contain cassiterite and numerous sulfide minerals, including stannite. The main characteristic that allies all the veins, however, is the high content of fluorite and beryllium. In some veinlets that contain up to several percent of tin, granular

fluorite is abundant, and the beryllium content ranges between .15 and .48 percent BeO, which is similar to that in the zones marginal to the tin ore shoot at the Lost River mine and at the Bessie-Maple area. In these veins, the fluorite is colorless, and there is often a high percentage of todorokite (as much as 10 percent manganese).

Around the granite, especially on the northwest margin, banded fluorite-magnetite skarn, locally with plagioclase, hornblende and other contact minerals, forms replacement veins and irregular masses up to a few feet across. They are described by Knopf (1908, p. 45). Jahns (1944a, p. 79) showed that a specimen of this rock contained a highly anomalous amount of beryllium, and has discussed the mode of formation of similar rock at Iron Mountain, New Mexico (Jahns, 1944b, p. 173-205). At greater distances from the granite, tactite consisting principally of andradite, magnetite, and vesuvianite (idocrase) forms irregular masses not more than a few hundred feet across. Such tactites are generally low in beryllium, except where cut by fluorite veinlets. The vesuvianite, however, has a notable content of beryllium. Although the banded skarn locally contains up to 0.45 percent BeO in helvite, the helvite is irregularly distributed, and the tonnage of beryllium-bearing skarn is too low to be of economic value.

The relations at Tin Creek demonstrate that some beryllium was contained in the fluids that transported large amounts of iron and fluorine during the stage of formation of skarn. That the skarn locally is cut by later veinlets richer in beryllium and containing tin and sulfide minerals, argues that the amount of beryllium in the fluids increased notably during the later stage of vein formation.

In the scheme of zonation illustrated in figure 42, the veins at Tin Creek are believed to be transitional between the cassiterite-sulfide deposits and the beryllium-fluorite deposits that contain no sulfides, but only hematite and todorokite. An anomalous situation at Tin Creek is the general absence of fluorite-beryllium veinlets around the northeast end of the granite, where cassiterite-bearing greisen has replaced the granite. Elsewhere, such greisens are bordered by a network of veinlets containing fluorite, chrysoberyl, and tourmaline.

Camp Creek.--By far the greatest amount of beryllium-fluorite rock in the district is exposed in the lode system in the drainage of Camp Creek, near the Lost River tin mine. The lode was discovered by the writer in late 1962, and in 1964 the U.S. Bureau of Mines explored the main part of the deposit by diamond-drilling, which proved a wide zone of beryllium-fluorite veins and veinlets over a length of some 2,400 feet. The eastern extension is not yet explored. The general geology is shown on figure 36 (in pocket). The drilling done to date suggests that the lode is complex, but in gross outline it forms a tabular body dipping south beneath the Rapid River fault. A lower thrust fault, the Camp Creek thrust, is marked by extreme brecciation and porosity, and the beryllium-fluorite veins are more numerous and wider in the porous zone. Individual veins and veinlets are localized by a strong fracture system that forms locally a sheeted zone dipping almost vertically beneath the Rapid River and Camp Creek faults, by closely spaced joints in the limestones, and by the brecciated limestones. Whether the individual veinlets continue

at depth to the granite that underlies the Lost River tin mine, or whether they are confined to the brecciated rocks beneath the Camp Creek and Rapid River faults cannot yet be answered. By extrapolation from the Rapid River deposits, it is most possible that individual veinlets continue beneath the thrusts, but that these veinlets are more numerous near the thrusts, and form an enriched tabular deposit dipping gently south, possibly as far as the dike swarm to the south (see figure 2). In figure 41, the relations at Rapid River and the probable configuration of the Camp Creek lode system are shown schematically.

Within the explored part of the Camp Creek lode, only a few discontinuous dikes have been found; they include rhyolite porphyry and lamprophyre. Where the Camp Creek lode system approaches the Cassiterite dike (see figure 36) float runs of rhyolite are associated with abundant float of beryllium-fluorite rock, elsewhere rich ore is found without associated dikes.

Mineralogically, the ores in Camp Creek consist of fluorite, diaspore, tourmaline, muscovite, chrysoberyl, hematite, and todorokite. The late veinlets of diaspore are rich in beryllium. Some drill cores from the central part of the lode intersected sulfide minerals that include pyrite and stannite. These sulfide-bearing zones are bounded by the usual beryllium-fluorite rock. At the extreme east end of the mineralized area (east of figure 36), a prospect first described by Knopf (1908, p. 60) contains stibnite, fluorite, and diaspore without beryllium minerals. In this area are numerous float runs of purple fluorite with

FIGURE 4/ PROBABLE CONFIGURATION OF ORE LOCALIZED
BENEATH THRUST FAULTS

non-beryllian diaspore. A few round nodules, similar in outline to those in the main beryllium lodes (see photo, figure 34b), are found, but these consist of a core of granular fluorite with stibnite, surrounded by white diaspore, and coated by a rim of lilac-colored fluorite. The beryllium content of the nodules is low.

The deposits in Camp Creek demonstrate a zonation along their strike, which is shown by the progressive decrease of beryllium minerals (and total beryllium), mica, and todorokite. The diaspore becomes non-beryllian at the outer end, where the low-temperature mineral stibnite makes its first appearance. In this interval, fluorite changes from the fine-grained, colorless variety to the coarsely crystalline colored variety, a relation also observed elsewhere in the district. The sulfide minerals encountered in drill holes are similar to those at the Bessie-Maple deposits, and they lie in the central part of fluorite-beryllium veins.

Lost River Mine.--Little time was devoted to the study of distribution of beryllium in the Lost River mine, because of time restrictions, because the lower levels of the mines are flooded, and because the upper levels are partly filled with ice. However, some of the mine workings were accessible, and a suite of samples was available from previous work.

Throughout the mine area, the limestone is cut by innumerable veinlets ranging from a hairline to a foot in thickness. These veinlets include tectite, the usual banded fluorite-diaspore-chrysoberyl veins, and quartz-topaz veins, some of which contain mica and cassiterite, and one of which contains mica and beryl. The large quartz veinlets cut the banded fluorite veins, and are later.

Beryllium occurs in the mine principally in a fluorite-tourmaline-cassiterite rock that forms selvages between the greisen of the tin ore shoot and the limestone wallrocks. Locally the selvages contain garnet and pyroxene with pyrrhotite, and are as much as three feet thick. In these selvages, beryllium amounts locally to an estimated 0.5 percent BeO , only part of which is in the form of chrysoberyl, and the tin content reaches as much as 3.3 percent. The tin is in cassiterite and subordinate stannite. The change in mineralogy along the strike of the selvages is unknown, for the surface exposures are high above the tin ore shoot where exposed by the mine workings, and the eastern end of the mine workings is inaccessible. For this reason, it was impossible to trace a single selva over long distances, where mineralogical changes could be observed.

Based upon analogy with greisen deposits near Mt. Antero, Colorado (Sharp and Hawley, 1960, p. 373-374), one might expect to find beryllium minerals in the topaz-greisen of the Lost River mine. Numerous pieces of greisen on the dumps at the mine were checked with the beryllium detector, and none were found that contained detectable beryllium. At Mt. Antero, the greisen pipes formed in granite or gneisses which are cut by quartz-pegmatite veins containing beryl, and Sharp (personal communication, 1965) feels that the bertrandite in the greisen represents remobilized beryl that furnished beryllium to the greisen. At Lost River, the lack of beryllium minerals in the greisen may reflect the lack of such a pre-existing concentration of beryllium. The fact that the greisen is bordered by beryllium-bearing fluorite suggests, however, that beryllium was

available during greisen formation, and that further detailed search will reveal at least local concentrations of beryllium minerals in the greisen, as were found by Ganiev (1961) in greisen in Central Tadzhikistan, Russia.

The granite cupola below the Lost River mine is locally greisenized, and locally argillized. The beryllium mineral phenakite has been identified from drill cores from this altered granite (Heide, 1964, p. 25), but the core is no longer available, and it cannot be determined whether the argillized rock represents altered granite or altered greisen.

The Zonal Concept of Tin-Beryllium Deposits

The relations described above permit the development of a concept of a zonal distribution of beryllium deposits around tin deposits in carbonate rocks that goes considerably beyond the general relations discussed by Beus (1962, p. 87-97), who notes the general association of skarn-type beryllium deposits with tin or tungsten deposits associated with granites that contain abnormal amounts of fluorine. Although many minor variations probably exist, the main spatial and mineralogical characteristics of the zones are summarized in figure 42. It is noticed immediately that the zonation involves sulfide minerals, non-sulfide ore minerals, such as chrysoberyl, and gangue minerals. As emphasized by Park (1957, p. 480), the gangue minerals and non-opaque ore minerals are critical in establishing the zonation. Study of the opaque ore minerals alone probably would not result in the recognition of the marked zoning.

In the scheme of zones, the skarn zone may occur without either the greisen or the beryllium-fluorite zones, but not enough areas have been examined to determine decisively whether the banded magnetite-fluorite skarns that contain helvite do not always have an outer zone of fluorite-beryllium veins. It is also to be remembered that the skarns here noted are those skarns that contain a high percentage of magnetite and fluorite, and that are at least in part rhythmically banded. In such skarns, the magnetite usually contains tin. On the other hand, it is doubtful if any tin-bearing greisen of the Lost River type can occur in limestone without being surrounded by the beryllium-fluorite zone.

ORE GENESIS

Using the information from the chemical analyses that show that ionic exchanges involved in creating ore from limestone (table 6) and the relatively constant mineralogy of the banded fluorite-beryllium ores and greisen deposits, we may conclude that ore deposition occurred in a system similar to the system $\text{BeO-Al}_2\text{O}_3\text{-H}_2\text{O-K}_2\text{O-Na}_2\text{O-CaO-F}$. Such a system is too complex for duplication in bomb studies, and no studies involving all these components, or five of them, have been made. Therefore, the application of laboratory studies of silicate systems to the problem of ore genesis can be used only as a general guide. Such studies, however, offer valuable information in explaining features observed in the ores. The mineral diaspore is critical,

for it occurs as a stable phase without corundum or kaolinite throughout the fluorite-beryllium ores. The fact that kaolinite does not occur is striking, for in the system $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$, kaolinite and diaspore are stable together over a temperature range from 280°C. to 405°C. at 10,000 psi water pressure (Roy and Osborne, 1954, p. 879). The conditions that might account for this can be explained by chemical composition or by temperatures, or by both.

From the fact that silica was available in the ore solutions, as well as in the argillaceous limestone, we may assume that silica was available for formation of kaolinite, as was water, and the absence of kaolinite must be explained otherwise.

If the temperature were the principal factor governing the formation of diaspore without kaolinite, the temperature of formation would lie between the limits bounded by the upper stability limit of diaspore, which varies from 385°C. at 2,000 psi to 415°C. at 20,000 psi, and the temperature of the inversion diaspore-boehmite, which occurs at 280°C. at 2,000 psi (Roy and Osborne, 1954, p. 879). Because the stability range of kaolinite extends from room temperature to 405°C. at 10,000 psi, a temperature range only between 405°C. and 415°C. can be allowed if temperature alone governed the relations between diaspore and kaolinite. Such a restricted range of temperature seems improbable over the time in which ores deposited, and hence alternative explanations must be called upon.

As shown by the analyses of the ore in table 6, Na_2O and K_2O were added to the limestones in an amount approximating 8 grams per 100 cc. of ore, a substantial amount. East of the Lost River mine (outward from the tin greisen deposits), the Cassiterite dike was altered to a quartz-adularia rock, which shows that K_2O was migrating outward from the greisen, beyond the zone of deposition of the greisen ores which contain abundant sulfide minerals. The lack of kaolinite can now be explained by reference to laboratory work by Hemley (1959), who investigated the system $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$. Hemley found that the stability relations between kaolinite and mica were influenced very strongly by the relative concentration of K^+ to H^+ ions in the solution. A high ratio of K^+/H^+ greatly enlarged the stability field of K-mica at the expense of kaolinite, especially near the upper stability temperature of kaolinite. If the ratio K^+/H^+ were high in the ore solution discussed here, as indicated by the addition of K_2O and Na_2O to the ore, the absence of kaolinite can be explained on chemical grounds that fit the known facts.

In the beryllium-fluorite envelope around the greisen deposits, tourmaline becomes abundant, and hematite is characteristic, indicating that the sulfur concentration decreased noticeably from its concentration during formation of the greisen ores. The greatly increased amount of tourmaline in the fluorite-beryllium ores over the amount in the topaz greisens could represent increasing alkalinity of the ore fluids, for the

hydrothermal synthesis of tourmaline requires alkaline or mildly acidic conditions (Smith, 1949). It is suggested here that the deposition of sulfur in the sulfide minerals in the greisen, and the reaction between solutions and carbonate wall rocks, without concomitant deposition of K, increased the K⁺/H⁺ ratio of the solutions, thus preventing the formation of kaolinite even though the temperature was within its stability field. The drop in acidity also allowed the increased formation of tourmaline in the fluorite-beryllium lodes. A gradual drop in acidity of the solutions accompanied the reaction between fluorine ions (or complexes) and the limestone wallrocks, e.g.,

This reaction forms a strongly buffered solution which would tend to maintain its pH over considerable distance in the hydrothermal conduit.

At the outer ends of the beryllium-fluorite lodes, the ore solutions cooled, although remaining above the temperature of the transition point diaspore-boehmite (300°C. at 2,500 psi and 275°C. at 20,000 psi), and the mineral stibnite was deposited with fluorite and diaspore. At the outer ends of the veins, continued abstraction of fluorine by reaction with carbonate to form fluorite, allowed continuing breakdown of SiF_4 by hydrolysis to produce the fine-grained silica and fluorite, e.g.,

From the relations between lamprophyres and granites, the chemical and mineralogical characteristics of the various ores, and the structural history of the central York Mountains, the evolution and genesis of the tin-beryllium deposits can be summarized as follows, initial events first:

1. Development of a tectonic belt in pre-Late Cretaceous time dominated by imbricate thrust faulting that carried younger rocks northward over older rocks.
2. Generation and injection of granitic magma in the tectonic belt, probably accompanied by normal faulting of the thrust plates, and injection of dikes of granitic composition into faults and fractures.
3. Cooling of the upper parts of the granites, without loss of late-stage fluids in the form of pegmatite.
4. Continued or renewed normal faulting, especially in a zone of faults striking N. 60°-85° E. through the central York Mountains, with concomitant injection of lamprophyre dikes, derived from deep-seated basaltic rocks, into some of the normal faults. Near granites, these basaltic rocks acquired xenoliths and xenocrysts of granite.
5. Escape of fluids from deep parts of granites along dikes and normal faults that penetrated deeply. These fluids contained numerous metals probably in the form of stable complexes of fluorine, chlorine,

boron and possibly sulfur, and were probably alkaline or at most mildly acid (Korsinsky, 1959, p. 17-20, Helgeson, 1964, p. 1).

6. Cooling of the ore fluids at least to 600°C., and deposition of tin and tungsten in the form of cassiterite and wolframite along with numerous other sulfide minerals, topaz, muscovite and fluorite, generally in or near granites or dike rocks. Loss of fluorine from solution to wall rocks during formation of topaz and fluorite, and addition of sodium and potassium to the solutions from altered wallrocks, caused rapid chemical changes in the solutions.

7. Entrance of the solutions into limestone, where the formation of fluorite from limestone increased the alkalinity of the solutions and led to deposition of beryllium minerals, diaspore, white mica, tourmaline and minor other minerals. The high ratio of K⁺ to H⁺ ions prevented formation of kaolinite. Ore shoots were localized in porous zones along the thrust faults.

8. Continued movement of solutions outward in veins in limestone, where the last minerals deposited were fluorite and chalcedonic silica.

9. Renewed normal faulting, which ruptured some of the ores, e.g., the tin ore shoot of the Lost River mine.

10. Uplift and erosion, with formation of placer deposits of cassiterite, which were removed periodically by glacial scouring.

DISTRIBUTION OF RARE ELEMENTS

Quantitative and semiquantitative spectrographic analyses were made of rocks and minerals from the central York Mountains to establish the geochemical fractionation of rare elements within the

granites, and the general content of rare elements of the rocks of the district. In tables 9 to 11 are shown the content of rare metals by class of rocks, as follows: sedimentary, metamorphic, granite stocks, dike rocks. In table 10 (in pocket), the distribution of the rare elements within the granites is shown, and in table 12 (in pocket), the rare element content of a few purified minerals from tactites near the granites is shown. In all the tables, the elements of interest are Be, Li, Sn, W, B, Cu, Pb, Zn, and Nb. In some tables, Ag and As as well are of interest. Because the detection limit of tungsten is relatively high (100 ppm), only a few samples contained detectable tungsten. In some cases, it proved impossible to prepare pure or reasonably pure minerals from the granites, and in such cases, no data are presented. In all cases where data are presented for pure minerals, the mineral purity was checked by X-ray diffractometer tracings.

Discussion

In the sedimentary rocks, the content of rare elements is comparable to average values reported by Turekian and Wedepohl (1961, p. 187) for similar rocks, with these general exceptions: niobium is slightly low, and boron is lower in the slate than in comparable unmetamorphosed shales. The noticeable large increase of boron, beryllium, lithium and tin in the hornfels from the contact area of the granite of Brooks Mountain indicates that these elements were migrating outward from the granite.

In the granite stocks, the total content of rare elements, particularly beryllium, tin, and boron, is considerably above the

average of granite as given by Turekian and Wedepohl, and the beryllium content is well above the average of granites of all types as noted by Beus (1962, p. 26), who gives an average content of beryllium of .0004 percent in biotite granites. Shaw and Bernold (1964, p. B100-B104) point out that the beryllium content of igneous rocks may be a function of the depth of crystallization, and they give an average Be content for nonpegmatitic plutonic silicic rocks of .00038 percent, with a range from 0 to .0030 percent. The high rare element content of the granites from the Seward Peninsula is confirmed by both quantitative and semiquantitative spectrographic analyses, and with regard to beryllium and tin, it represents a high level of concentration.

Within the granites, the distribution of rare elements among minerals is in general conformable with relations observed by other workers. One notes immediately that the content of all elements of interest rises sharply in the high-gravity fractions which contain the accessory minerals. Beus (1962, p. 28-30) notes that beryllium is enriched in some rare earth minerals, such as allanite and eudialyte. On the other hand, Lee and Bastron (1962, p. 1329) separated allanite from a quartz-monzonite stock in the Snake Range, Nevada, near which there are some beryllium deposits, and found no detectable beryllium. Lee also cautions that most of the allanites reported to contain

a high content of beryllium are from pegmatites, and that many (oral communication, 1965) are badly altered or metamict. In the Seward Peninsula granites, detectable tungsten appears only in these heavy-mineral fractions. Oftedal (1961) shows that in Norwegian granite pegmatites, tungsten is highly enriched in minerals of niobium and tantalum, and that the saturation limit in these minerals is seldom reached. He further notes that no tungsten minerals are known in the granite pegmatites.

The biotites were separated and analyzed principally to determine if they could be the source of the heavy metals furnished to the tin deposits. The biotite from the granites contains (average of 5 samples) .0010 percent Be, the same as biotite separated from granite in eastern Transbaikalia, Russia (Beus, 1962, p. 27) that contains considerably less beryllium (.0008 percent Be). The content of Pb and Zn is comparable to that in biotite from granitic plutons in Nevada (Parry and Nakowski, 1960, p. 174), and the copper content of the biotite is much lower. With respect to copper, it has been shown that copper does not occur in the lattice of the main minerals of igneous rocks, but principally in the mineral chalcopyrite (Wedepohl, 1963). Parry and Nakowski state that the high copper values obtained from biotites in the Basin and Range province was probably due to inclusion of chalcopyrite, and the great increase of copper in the heavy mineral fractions

of the granites from the Seward Peninsula suggests that there is "accessory" chalcopyrite. A sample of bleached biotite from the granite beneath the Lost River mine contains as much of the rare elements as unbleached biotite from the other granites, indicating no great loss of rare metals during the bleaching. It has been shown by Bujor (1943) that biotite can be bleached by acid fluids without great loss of elements, whereas biotite acted upon by alkaline fluid is dissolved. As the granite at Lost River was altered by the fluorine-bearing solution that formed the topaz greisens, a solution presumably at least mildly acid, the preservation of rare elements in the bleached biotite may be explained. Theobald and Havens (1960, p. 223) have shown that the base metal content in biotite in an altered sill in Summit County, Colorado, increased during alteration from biotite through iron-poor chlorite into muscovite. The literature suggests that a major transfer of heavy elements out of biotite in a hydrothermal environment would require actual dissolution of the biotite, and not merely bleaching or gradual translation into other micas. If so, alkaline solutions possibly would be required. The tin content of the biotites from the Seward Peninsula (average .026 percent) is about 10 times the content of the most tin-rich biotites found by Putnam and Burnham (1963, p. 87-106) in the several stocks

in Arizona sampled by them. In their study, they found that biotite from the Payson granite contained an average of .0023 percent tin. As is true with beryllium, the occurrence of tin deposits near the granites of the western Seward Peninsula is correlative with an unusually high tin content of the granites, and especially of biotite in the granites.

It should be noted that the tin content of the biotites from the granites is well below the tin content of muscovite mica from pegmatites, but well above the content in biotites from pegmatites in those specimens analyzed by Ahrens and Liebenberg (1950, p. 575), who found a maximum of .013 percent SnO_2 (about .010 percent Sn).

The beryllium content of quartz separated from the unaltered granites ranges from below detection limits (.00015 percent) to .0005 percent, considerably above that reported by Seus (1962, p. 27) for quartz separated from Russian granite (.00002 percent), but still well below the average content of the granites. The X-ray patterns of the two samples of quartz that contain detectable beryllium indicate that they contain a small amount of plagioclase which could not be separated, and hence the larger values probably represent contamination by plagioclase. The tin content of the quartz is generally below detection limits (.001 percent), but reaches .003 percent in one sample.

In the feldspars, the distribution of beryllium between the orthoclase and plagioclase (generally albite or oligoclase)

indicates a slight preference of beryllium for orthoclase, although one reversal is noted (Brooks Mountain). Warner, et al (1958, p. 19) note the same general relations in feldspars from other areas. The slight enrichment of beryllium in the feldspars over the granite as a whole offsets the impoverishment in the quartz. With respect to copper, the data suggest a preference for orthoclase, although copper is enriched most in the heavy mineral fractions. With respect to Pb there is a distinct enrichment in plagioclase, approximately seven-fold when averaged.

With respect to niobium in all the samples, a clear-cut enrichment in biotite and in the heavy mineral fractions is indicated, whereas the content in plagioclase, orthoclase and quartz is less than that in the granite.

In dike rocks, the fractionation among dike types of the rare elements listed follows rules which can now be considered commonplace, e.g., the light elements are lacking in the diabase dikes, whereas copper is higher than in the granites. In the lamprophyre dikes, the beryllium content is explained by the xenocrysts and xenoliths of granite, and is higher than in the diabbases. The high beryllium content of D100125 (.015 percent) is owing to the location of this dike in the midst of the younger beryllium deposits on Rapid River, and this dike has probably been altered by the ore-bearing solutions. In altered dikes that lie near the tin deposits of the Lost River mine, the content of tin

increases as expected, as does beryllium, lithium or boron. Most of these dikes contain megascopic amounts of fluorite, white mica or tourmaline, and have been altered by the mineralizing solutions that formed the tin deposits.

The vesuvianite (idocrase) and garnet samples were separated and analyzed to give an idea of the degree of rare element entry into these minerals from an area where beryllium was present in high concentration in the granites. As noted by many workers (see Warner, et al, 1959, p. 17-18 for summary), idocrase in places contains as much as 3.95 percent BeO. The idocrase at Iron Mountain, New Mexico, where there are beryllium deposits, contains 1.09 percent BeO. Consequently, it was surprising to find only .05 percent and .005 percent BeO in idocrase from Tin Creek and Brooks Mountain, respectively. The X-ray patterns of these samples indicates absolute purity. The grossularite garnet from Iron Mountain contains BeO in the range .06-.19 percent, noticeably higher than the single garnet tested from Tin Creek (.0003 percent BeO). As numerous veins or veinlets of fluorite-beryllium rock, as well as helvite-bearing fluorite-magnetite "ribbon rock", occur around the granite of Tin Creek, one must assume that during formation of the contact rocks at Tin Creek, beryllium was not available in amounts as large as at Iron Mountain. This also accounts for the small amount of helvite in the skarns at Tin Creek. Most of the beryllium was added during a late period of mineralization.

Of the minerals separated from the beryllium ores, the tourmaline, mica, and diaspore accepted large amounts of beryllium.

Warner, et al (1959, p. 18), and Beus (1962, p. 36) show that tourmaline may contain as much as .0X percent BeO. Without intensive literature search, I have found no analyses of diaspore showing the rare element content. As the diaspore and tourmaline discussed here grew in a solution presumably saturated with beryllium, they probably accepted all the beryllium possible, and hence their contents of .7 percent and .3 percent Be may be maximum values. However, even though the optical and X-ray data indicate that these minerals were pure, they were separated from an extremely fine grained ore, and some of the Be may be accounted for by discrete beryllium minerals. The tourmaline exhibits absolutely no absorption or dichroism, with variable indices of refraction $E = 1.624 \pm .05$, $W = 1.637 \pm .05$.

The high beryllium content of the mica is interesting, but again the separated mica could contain a small amount of bityite to account for the high content of BeO. In pegmatites, micas have been found to contain up to .0X percent BeO by Goldschmidt and Peters (1932, p. 366), and Beus (1962, p. 36) states that lepidolite and muscovite mica from pegmatites that contain beryllium minerals may contain up to .0126 percent beryllium, considerably below the white micas (3 samples) separated from the beryllium ores (minimum of .07 percent Be). On the other hand, Eitel, Hatch and Humphrey (1950) have synthesized fluorine-phlogopite in which one-quarter of the silicon is replaced by beryllium by diadochic substitution of $Be^{2+}Si^{4+}$ for $Al^{3+}Al^{3+}$ in tetrahedral coordination. This gives a BeO content of about 3

percent, well above the highest concentration observed in the white mica separated from the Rapid River ores (1.96 percent BeO). More work will be done on the individual minerals from the ores to confirm the content of beryllium and other elements.

Summary of Distribution of the Rare Elements

From the above discussion, we may conclude that the general increase in rare elements, especially the light elements, accompanied the intrusion of the granites. The lamprophyre dikes acquired beryllium through ingestion of granite. Within the granites, the distribution of rare elements generally parallels the distribution observed elsewhere. But even though the granites are abnormally rich in beryllium, the earliest skarns and tectites that presumably formed during the crystallization of the granites contain less beryllium than observed at other places, e.g., Iron Mountain, *New Mexico*.

The mineralizing stage followed the intrusion of lamprophyre dikes, low in silica and light elements, which were injected into fractures of a regional fault system which cut the exposed granites. A significant time must have elapsed between the consolidation of the exposed granites and the entrance of mineralizing solutions that formed the tin and beryllium ores. During this time, rare elements and volatiles presumably concentrated in deeper parts of the granites, and the faulting and entrance of the lamprophyre dikes fractured the cooled shell of the granite, allowing escape of these volatiles and rare elements into the overlying rocks, where significant ore bodies of tin, beryllium, and fluorite formed. The complete absence of pegmatites in the western Seward Peninsula indicates that little

of the residual water and volatile-rich fluid that concentrated during crystallization escaped to form pegmatites, thus contributing to a very volatile-rich phase. Following Shaw's suggestion (1961, p. 3100) that increased beryllium content of silicic rocks can be directly correlated with the depth of crystallization, it is possible that the Seward Peninsula granites were emplaced well below the surface.

ECONOMIC GEOCHEMISTRY

Rare Elements in Supergene Processes

During the weathering and decay of the granites, lodes and contact rocks, clearcut geochemical anomalies were formed in stream sediments, soils and plants of the area. In the initial stage of this study, reconnaissance of the granites of the western Seward Peninsula showed anomalous beryllium in stream sediments around the granites, and use of this data contributed to the discovery of large beryllium lodes (Sainsbury, 1963, p. 12-15). The various dispersion halos which may prove of value in exploration here and elsewhere are discussed as economic geochemistry, although the information is of scientific interest as well. In the following discussion and tables, the trace metal content is expressed as parts per million (ppm) to conform with accepted practice in geochemical prospecting.

Stream Sediments

In the report referred to above, maps were presented showing the beryllium content of stream sediments from various areas in the western Seward Peninsula (p. 12-16). From these and other

samples collected since 1960, it has been determined that the beryllium content of total stream sediments less than 40 mesh in size varies with the rock type within the drainage basin of the streams. In areas of limestone, the background content of beryllium probably does not exceed 1.5 ppm (parts per million) of beryllium, and definitely is below 3 ppm. Where granite underlies a considerable part of the drainage basin, the beryllium content in sediments may approximate that of the granite (up to about 18 ppm). Hence a value that definitely is anomalous in one area is not so in another, and these differences should be kept in mind during geochemical prospecting. For a more detailed discussion of the variation in beryllium content of stream sediments that represent diverse geologic terranes in the Oslo region, Norway, see Brinck and Hofmann (1964), who show that there is substantial variation between sediments from different rock units.

In limestone areas a beryllium content in the range 3-5 ppm might be termed the threshold value and beryllium in the range 5-10 ppm definitely is anomalous. The maximum values to be expected in sediments will, of course, be a function of the size of the drainage basin, the amount and richness of ore bodies exposed at the surface within the basin, and their nearness to the stream. An upper value to be expected in the Seward Peninsula, and probably elsewhere in the Arctic and sub-Arctic, where mechanical disintegration predominates over chemical decay, should approximate the values obtained in Camp Creek, where a long and continuous lode system outcrops in the small drainage basin (see figure 31). In this small

stream, beryllium in total stream sediments reached a maximum of 160 ppm, and all samples were above 100 ppm. Large and small boulders of fluorite-beryllium rock form a significant proportion of the bed load, and these contain beryllium in the range .2-1.75 percent BeO.

In Tin Creek, a stream that contains both granite and beryllium-fluorite lodes within its drainage basin, sediments contain beryllium in the range 10-30 ppm, the highest value being found in sediments downstream from the area of marble that contains numerous veinlets of fluorite-beryllium rock (see figure 40).

In Rapid River, where a mineralized belt in limestone crosses the stream, sediments contain as much as 16 ppm beryllium (see figure 37), and values fall off rapidly to less than 3 ppm within a mile downstream.

On the other hand, stream sediments from the east headwaters of the Mint River, which drains the southwest margin of the granite of Brooks Mountain, consistently contain more than 13 ppm beryllium, yet careful search has failed to find significant fluorite-beryllium lodes. The apparent anomaly is explained by the high content of granite in the stream sediments, and by the rather large volume of idocrase from the contact zone of the granite. The granite contains 15 ppm beryllium, and the idocrase as much as 50 ppm beryllium.

The form in which the beryllium is transported in stream sediments has not been determined. Near lodes, discrete fragments of ore can be found, but owing to the softness and friability of fluorite, the ore breaks up rapidly. On the other hand, diaspore and chrysoberyl are both hard and chemically resistant, and discrete

fragments of these materials have been found in sediments well downstream from the lodes. If these fragments persist for long distances, a technique suggested by Vance Kennedy (oral communication), 1964, might extend the distance over which beryllium deposits could be found in limestone areas. Vance suggested that acid leaching of the carbonate fraction of sediments would enrich the residue in beryllium to such an extent that the field method (Patten and Ward, 1962) could detect beryllium well below 1 ppm. This suggestion has merit, and will be investigated.

To determine the geochemical association of rare elements in sediments, more than 100 samples were analyzed for beryllium, tin, molybdenum and tungsten, and 17 of these were analyzed by semi-quantitative spectrographic analyses for these and other elements. Only the results of the spectrographic analysis are shown in table 13, from which it is seen that the rare elements that are associated in the igneous rocks and in the tin and beryllium lodes are also associated in the stream sediments, with the exception that zinc and niobium are quickly reduced below their detection limits. A direct correlation exists between tin, tungsten, arsenic and lead. Although most samples high in tin and tungsten contain anomalous beryllium, the highest values for beryllium are from samples that contain less than the maximum tin, tungsten, lead and arsenic. This follows as a result of the zonal distribution of tin-tungsten-base metal lodes, and the beryllium fluorite lodes which shed detritus to different streams.

Soils

To determine the applicability of geochemical sampling of soils to find and outline the beryllium lodes in limestone, soil samples were taken in Lost River valley in two long lines that cross the mineralized zone along the Rapid River fault (figure 39). Control samples were taken far from mineralized areas to establish background values. In Lost River valley, bedrock along the traverse lines is veneered thinly by frost-broken limestone bedrock, upon which a thin residual soil is developing. Tundra clumps cover possibly 30-50 percent of the ground surface. Between tundra clumps, the soil has a thin veneer consisting of yellow to reddish clay and limestone pebbles. Beneath the clay-pebble zone, yellowish clayey soil between 1 and 2 inches thick overlies frost-broken bedrock. All the soil samples came from the yellow clay zone without pebbles. A clump of tundra was taken from the tundra nearest each soil sample, generally within 2 feet. The location of soil samples, and the content in parts per million of beryllium, copper, lead and zinc, is shown on figure 39. The control samples are off this figure, and were collected in the area around the mouth of Bach Creek (figure 2) that enters Lost River from the west about 1 mile north of the area of figure 39. Table 14 (in pocket) gives the numbers and metal content of all the samples in tabular form, and identifies the analytical method used.

From the table and figure 39, one sees that the background values of beryllium, copper, lead and zinc in soils is (average of 4 control samples), in parts per million; Be, 2; Cu, 21.5; Pb, 44; Zn, 90.5. The ranges are Be, 2; Cu, 17-27; Pb, 35-50; Zn, 50-140. The values

obtained from soils near veined limestone along the Rapid River fault contain highly anomalous amounts of beryllium, copper, lead and zinc. Beryllium is enriched locally by a factor of 100, copper by 34, lead by 48, and zinc by 55. The heavy metals most probably are held by cation exchange in lattices of layered silicates of the clay minerals groups, a relation that has proved common (Beus, 1962, p. 41; Warner, et al, 1959, p. 28). The heavy metal anomaly is broad along the east side of Lost River valley, where the Rapid River fault curves north, and where small remnants of a lateral moraine from the glacier that filled Lost River valley remain locally. Beryllium-rich material from Camp Creek and the area of the Lost River mine was incorporated in this moraine. On the west side of Lost River valley, where the Rapid River fault is at right angles to the valley, the anomaly is narrower, and rare metal content approaches background values more closely. Glacial moraine on the west side of Lost River would have contained little beryllium-rich rock.

The above data are sufficient to show that geochemical mapping by use of soil sampling would be capable of outlining mineralized areas in limestone.

Plants

Beus (1962, p. 42) notes the paucity of information on beryllium in plants, and suggests that more data are needed. Additional data is presented here.

The tundra clumps that were collected along the traverses in Lost River valley were washed repeatedly, ashed by heating gradually to 500°C. in porcelain crucibles, and analyzed by semiquantitative

spectrographic analyses. In some clumps the different plants were separated and analyzed individually to see if such plants preferentially enriched certain elements. The plants were identified by Dr. Hansford T. Shacklette, botanist, U.S. Geological Survey. For the most part, the tundra clumps in Lost River valley consist of the plant *Arenaria arctica*, with minor amounts of the other plants listed.

Owing to the high winds and heavy rains which constantly coat the tundra plants with soil, much soil is permanently fixed to the growing plant. Even after repeated washings and massaging in distilled water, minute fragments of minerals could be obtained from many of the plants. Hence, it proved impossible to determine the quantitative enrichment of rare elements in plants. However, in tables 15 and 16 (in pocket), the rare element content of the ash is shown as the change in parts per million of the rare metal compared to the content of the soil on which it grew. Obviously, if the content in the ash exceeds the content in the soil, the plant has concentrated that element, even though the element is toxic to the plant (Wallace, 1961). As an additional check, the ratio of aluminum in the soil over the aluminum in the ash is shown. Where the ratio exceeds 1, soil contamination cannot have had a large effect in contributing rare elements to the ash. Furthermore, aluminum is a characteristic element of most plants (Wallace, 1961), and hence the alumina in plant ash may not be a result of contamination at all.

Inspection of the data presented in tables 15 and 16 demonstrates the following:

1. Several light and heavy elements are consistently enriched in the ash of bulk tundra clumps and specific plants, principally copper, lead and boron. These elements are enriched in plants growing on soil that contained the elements in amounts below their detection limit.

2. In most tundra clumps and in specific plants, silver was enriched, and zinc was highly enriched in plant ash.

3. Arsenic, beryllium, tin, and niobium tended to decrease in concentration in plant ash relative to the concentration in soils, although there are significant differences in behavior that are explainable for tin and, less so, for beryllium. In plotting the data, it became apparent that there was a point at which there was a systematic change for tin from apparent gain to apparent loss (negative value relative to the soil). Inspection of tables 14 and 16 shows that as long as the concentration of tin in the soil is below about 100 ppm, that the tundra ash enriches tin, but when the concentration in the soil exceeds 150 ppm, the concentration level in the plant ash is negative (minus sign in the tables). The same relation is true to a lesser degree for beryllium, for if the soil content is at or below 20 ppm, the tundra contains beryllium, even though beryllium is toxic to the plant. If the soil contains more than about 50 ppm, the plants cannot absorb more than the amount that gives this content in tundra ash (in fact, they may die and weather away), and as the concentration in the soil increases to high values, the plants therefore show a negative value in ash. The effect is that of two intersecting lines with different slopes, the

steeper being the concentration in soils, and the point of intersection being the point at which the plant cannot further increase its content of rare element, or at which its degree of concentration in ash falls below that in the soil. In the tables in this report, a plus sign for the elements tin and beryllium and to a lesser extent for niobium, signifies a point below the intersection, and a negative sign a point above the intersection.

In 1962, Ronney, Childress and Alexander (1962, p. 786, 787) demonstrated that beryllium in nutrient solution inhibited the growth of bush bean seedlings, caused early flowering, and led to enrichment in beryllium of parts of the plants, notably roots while producing certain toxic effects. The highest concentration of beryllium in dry plant (roots) reached 1,076 ppm in plants grown in solutions with 5 ppm beryllium in soluble form. Other workers (Zalashkova, Lisunov, and Sitnin, 1958), have shown that both soils and certain plants over beryl-bearing pegmatites contain anomalous beryllium. In plants, the highest value obtained was 39 ppm beryllium in ash from alder leaves. Griffiths (oral communication, 1965) has found that plants growing over beryllium deposits at Spor Mountain, Utah, and Aguachile, Mexico, contain beryllium up to a maximum of 150 ppm in ash.

The plants investigated by Griffiths are *Tetradymia glabrata* at Spor Mountain, and *Ephedra aspera*, *Mahonia trifoliata*, *Poliera(?)*, grass (*Andropogon* or *aristida*), *Helanias*, *Bahia(?)*, *Rhus virins*, *Acacia(?)*, *Euphorbia antisiphilitica* at Aguachile, none of which are present in tundra in Lost River, and hence direct comparisons are not possible.

At Lost River, the content of beryllium in plant ash reaches 150 ppm in Saxifraga, a value comparable to the greatest content found by Griffiths, but it is considerably less than that in cultured bush beans. Although identical species are not available from diverse areas, it is probable that the major factor in enrichment of beryllium is the form in which the beryllium occurs around the plant roots, and the toxicity of beryllium to that particular plant. Presumably beryllium is not in soluble form in natural soil water at Lost River in amounts comparable to the 5 ppm used by Romney, Childress and Alexander, for if so the soils probably would be flushed clean of beryllium.

h. The single lichen investigated (a long, wormlike, light, white lichen) rejected all metallic elements with the exception of silver, which it concentrated.

The elements, boron, copper and zinc, are well established as essential trace elements in plants (for summary, see Wallace, 1961, p. 12-14), and hence their ubiquitous presence is to be expected, even though they may be toxic in large concentrations. It is entirely possible that many of the plants reported here to contain anomalous amounts of rare metals were suffering from toxic concentrations of rare elements, but these effects were not looked for. It is also possible that many plants had been killed by toxic effects of rare elements, and had decayed away.

Summary

Most of the rare elements that are associated in the granite stocks and in the ore deposits of the district remain associated throughout weathering and transportation of elements in supergene

processes. The element zinc may be an exception in that it occurs in relatively low levels in the stream sediments, although the mineral ferroan sphalerite is a common mineral in the tin deposits. A possible explanation is that zinc is highly concentrated in the plants and residual clay soil, thus lessening its availability in the stream sediments that are within the size range generally sampled (-40 mesh). In spring and summer, much of the residual clay soil is lost during spring melting and in heavy rains, and is flushed to the ocean in high waters, leaving but a small percentage of the zinc-rich soil in the stream sediments.

The elements needed for plant growth (B, Cu, Zn) are concentrated in ash of all plants; those without established use patterns (Be, Nb, Sn) vary somewhat erratically, with the concentration level generally being a function of the concentration in the soil, and possibly of a level at which toxic effects kill the plant.

Water

The content of beryllium in waters free of colloidal material is very low (generally below .000001 percent), and well below the limits of detection by ordinary spectrographic procedures. However, as no analyses are reported from waters free of colloidal material from distinctly beryllium-rich deposits, it was deemed worthwhile to test the water from Camp Creek, which contains a large number of boulders and cobbles of fluorite-beryllium rock. Using the morin-fluorescence method (Patten and Ward, 1962), several samples of clear water from Camp Creek were tested in the field. Aliquots of

water to 10 times the recommended sample weight were used without detection of beryllium, from which it is inferred that the beryllium in solution in the water was less than .3 ppm (.00003 percent).

RECEIVED
FEB 10 1964
PANCASTER BOND

REFERENCES CITED

- Ahrens, L. H., and Liebenberg, W. R., 1950, Tin and indium in mica, as determined spectrochemically: *Amer. Min.*, v. 35, p. 571-578.
- Beus, A. A., 1957, Concerning beryllium idocrase: *Trudy*, v. 8, p. 25-28.
- _____, 1962, *Beryllium*: W. H. Freeman and Co., San Francisco, p. 1-61.
- Brinck, Johan, and Hofmann, Albert, 1964, The distribution of beryllium in the Oslo region, Norway - a geochemical stream sediment study: *Econ. Geology*, v. 59, p. 79-96.
- Brooks, A. H., Richardson, G. B., and Collier, A. J., 1901, A reconnaissance of the Cape Nome and adjacent gold fields of Seward Peninsula, Alaska, in 1900: *U.S. Geol. Survey Special Publication*, p. 1-222.
- Bujor, D. Jonescu, 1943, Elektronenmikroskopische Untersuchung der Montmorillonitbildung aus zersetzten biotiten: *Neues Jahr. für Min.; Geol., and Paleo., Monatshefte*, A, p. 25-32.
- Chatterjee, H. D., 1959, Die lamprophyre der spessarts und das Lamprophyre Problema: *Nachrichten Akad. Wissen. Göttingen II, Math. Phys. Klass Jahrg.*, no. 1, p. 1-24.
- Collier, A. J., 1902, A reconnaissance of the northwestern portion of Seward Peninsula, Alaska: *U.S. Geol. Survey Bull.* 358, p. 1-69.
- Cornec, M. Eugene, 1919, Etude spectrographique des cendres de plantes marines: *Comptes Rendus*, v. 168, 1, p. 513-514.
- Coradossi, N., and Tonani, F., 1961, Dosatura spettrografica del Berillio nelle granodiorite del Monte Capanne (Elba) e dell'isola del Giglio: *Atti Soc. Tosc. Sci. Natur. Pisa*: v. 68,

- ser. A., p. 1-22.
- Dutro, J. Thomas, and Payne, Thomas G., 1957, Geologic map of Alaska: U.S. Geol. Survey Miscellaneous Map, MR-802h.
- Eitel, Wilhelm, Hatch, R. A., and Humphrey, R. A., 1950, Isomorphism of synthetic fluorine micas: Amer. Cryst. Assoc., Abs. of First Meeting, State College, Pa., p. 17.
- Feigl, F., 1929, Quantitative microanalyses. III. Detection of thiocyanate, fluoride and copper, two methods of distinguishing between tap water and distilled water, detection of alkali in water, and a drop reaction for ammonia: *Mikrochemie*, v. 7, p. 10-20.
- Folk, R. L., 1959, Practical petrographic classification of limestone: *Am. Assoc. Petroleum Geologists Bull.*, v. 43, p. 1-38.
- Ganiev, I. G., 1961, Geochemistry of beryllium: *Geokhimiya*, No. 5, p. 446-452.
- Gruner, J. W., 1944, Simple tests for the detection of the beryllium mineral helvite: *Econ. Geology*, v. 39, p. 444-447.
- Goldschmidt, V. H., and Peters, Cl., 1932, Geochemie des Berylliums: *Gesell. Wiss. Göttingen, Math-phys. Kl. Nachr.*, Heft 4, S. 360-376.
- Heide, H. E., 1946, Investigation of the Lost River tin deposit, Seward Peninsula, Alaska: U.S. Bur. Mines Rept. Inv. 3902, p. 1-57.
- Hegelson, Harold C., 1964, Complexing and hydrothermal ore deposition: The Pergamon Press, Inc., distributed by the Macmillan Co., N. Y.
- Hemley, J. J., 1959, Some mineralogical equilibria in the system $K_2O-Al_2O_3-SiO_2-H_2O$: *Am. Jour. Sci.*, v. 257, p. 241-270.

- Hewitt, W. P., 1943, Geology and mineralization of the San Antonio mine, Santa Eulalia district, Chihuahua, Mexico: G.S.A. Bull., v. 54, p. 173-204.
- Jahns, R. H., 1944a, Beryllium and tungsten deposits of the Iron Mountain district, Sierra and Socorro Counties, New Mexico: U.S. Geol. Survey Bull. 945-C, p. 45-79.
- _____, 1944b, "Ribbon rock", an unusual beryllium-bearing tectite: Econ. Geology, v. 39, no. 3, p. 173-205.
- Jeffery, P. G., 1959, The geochemistry of tungsten, with special reference to the rocks of the Uganda Protectorate: Geochem. et Cosmo. Chem. Acta, 16, p. 278-295.
- Kindle, E. H., 1911, The faunal succession in the Fort Clarence limestone: Amer. Jour. Sci., Ser. 4, v. 32, p. 335-349.
- Knopf, Adolph, 1908, Geology of the Seward Peninsula tin deposits, Alaska: U.S. Geol. Survey Bull. 733, p. 1-130.
- _____, 1910, The probable Tertiary land bridge between Asia and North America: U. of Calif. Dept. Geol. Bull. 5, p. 413-420.
- _____, 1936, Igneous geology of the Spanish Peaks region, Colorado: G.S.A. Bull., v. 47, no. 11, p. 1727-1784.
- Korsinsky, D. S., 1959, The advancing wave of acidic components in ascending solutions and hydrothermal acid-base differentiation: Geochem. Cosmochem. Acta, 17, p. 17-20.
- Krauskopf, K. E., 1964, The possible role of volatile metal compounds in ore genesis: Econ. Geology, v. 59, no. 1, p. 22-45.
- Lee, D. E., and Bastron, Harry, 1962, Allanite from the Mount Wheeler area, White Pine County, Nevada: Am. Miner., v. 47, p. 1327-1331.

- Metals, D., and Chayes, F., 1963, Varieties of Lamprophyre; Annual Rept. of the Director of the Geophysical Laboratory, Carnegie Institute of Washington, for years 1962-63, p. 156-157.
- Hogárovskii, V. V., and Rossickin, L. V., 1961, Geochemistry of rare and dispersed elements at the Maikhura tin-tungsten deposit (Central Tadzhikistan): *Geokhimiya*, no. 6, p. 526-534.
- Mulligan, J. J., 1959, Sampling stream gravels for tin near York, Seward Peninsula, Alaska: U.S. Bur. Mines Rept. Inv. 5520, p. 1-25.
- Oftedal, I. W., 1961, Contribution to the geochemistry of tungsten: *Bull. Geol. Inst. Uppsala*, 40, p. 135-138.
- Park, C. F., Jr., 1957, The problem of vertical zoning: *Econ. Geol.*, v. 52, no. 5, p. 477-481.
- Falache, Charles, and Bauer, L. H., 1930, On the occurrence of beryllium in the zinc deposits of Franklin, N. J.: *Am. Miner.*, v. 15, p. 30-33.
- Parry, William T., and Mackowski, Matthew P., 1960, Base metals in biotites associated with ore deposits [Abstracts] G.S.A. Bull. Program Annual Meeting at Denver, Colorado, 1960, p. 223.
- Patten, L. E., and Ward, F. H., 1962, Geochemical field method for beryllium prospecting, Short Papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 450-C, p. C103-C104.
- Putnam, G. W., and Burnham, C. W., 1963, Trace elements in igneous rocks, northwestern and central Arizona: *Geochem. Cosmochem. Acta*, 27, p. 53-106.
- Roy, Rustum, and Osborn, E. F., 1954, The system $Al_2O_3-SiO_2-H_2O$: *Am. Mineral.*, v. 39, p. 853-886.

- Ross, R. J., 1965, Early Ordovician trilobites from the Seward Peninsula, Alaska: Jour. Pale., v. 39, no. 1, p. 17-20.
- Romney, Evan M., Childress, James D., and Alexander, George V., 1962, Beryllium and the growth of bush beans: Science, v. 135, p. 786-787.
- Sainsbury, C. L., 1960, Metallization and post-mineral hypogene argillization, Lost River tin mine, Alaska: Econ. Geology, v. 55, no. 7, p. 1478-1506.
- _____, 1963, Beryllium deposits of the western Seward Peninsula, Alaska: U.S. Geol. Survey Circ. 479, p. 1-18.
- _____, 1964a, Geology of the Lost River mine area, Alaska: U.S. Geol. Survey Bull. 1129, p. 1-80.
- _____, 1964b, Association of beryllium with tin deposits rich in fluorite: Econ. Geology, v. 59, p. 920-929.
- _____, 1964c, in Minerals and water resources of Alaska: Report prepared for Senator Ernest Gruening, Alaska, by the U.S. Geol. Survey and the State of Alaska Department of Natural Resources: U.S. Senate Document, Committee on Interior and Insular Affairs.
- _____, In press, Improved method for studying limestone in thin section: Jour. Sed. Petrology.
- _____, In publication, Quaternary geology of the western part of the Seward Peninsula, Alaska: for publication in Proc. VII International Congress for Quaternary Research, Symposium on the Bering Land Bridge.
- Sen, N., Nockolds, S. R., and Allen, R., 1959, Trace elements in minerals from rocks of the So. California batholith: Geochem. Cosmochem. Acta, 16, p. 58-72.

- Sharp, W. H., and Hawley, C. C., 1960, Bertrandite-bearing greisen, a new beryllium ore from the Lake George district, Colorado: U.S. Geol. Survey Prof. Paper 400-B, p. B73-74.
- Shawe, Daniel R., and Bernold, Stanley, 1965, Distribution of beryllium in igneous rocks: U.S. Geol. Survey Prof. Paper 501-B, p. B100-104.
- Shcherbina, V. V., 1962, On compounds in which elements are transported in geochemical processes: Geochemistry, no. 11, p. 1069-1076, translated from Geokhimiya, 1962, no. 11, p. 945-952.
- Silbermintz, B. A., and Roschkowa, E. W., 1933, Zur Frage des Vorkommens von Beryllium in Vesuvianen: Centralblatt für Min., Geol., und Paleo., Abt A., p. 249-254.
- Smith, F. G., 1949, Laboratory testing of "pneumatolytic" deposits: Transportation and deposition of the non-sulfide vein minerals. IV. Tourmaline: Econ. Geol., v. 44, no. 3, p. 186-192.
- Steidtmann, Edward, and Cathcart, S. H., 1922, Geology of the York tin deposits, Alaska: U.S. Geol. Survey Bull. 733, p. 1-130.
- Staatz, M. H., and Griffiths, W. R., 1961, Beryllium-bearing tuff in the Thomas Range, Juab County, Utah: Econ. Geology, v. 56, p. 941-950.
- Theobald, P. K., Jr., and Havens, R. G., 1960 [Abstract], Base metals in biotite, magnetite and their alteration products in a hydrothermally altered quartz monzonite porphyry sill, Summit County, Colorado: Program G.S.A. Annual Meeting, Denver, Colo., p. 223.

- Turekian, K. K., and Wedepohl, K. H., 1961, Distribution of the elements in some major units of the Earth's crust: G.S.A. Bull., v. 72, no. 2, p. 175-192.
- U.S. Bureau of Mines, 1963, Minerals Yearbook.
- _____, 1960, Mineral facts and problems; U.S. Bureau of Mines Bull. 585.
- Wallace, T., 1961, The diagnosis of mineral deficiencies in plants, by visual symptoms: Chemical Publishing Co., Inc., New York, N. Y.
- Warner, L. A., Halser, W. T., Wilmarth, V. R., and Cameron, E. N., 1959, The occurrence of non-pegmatite beryllium in the United States: U.S. Geol. Survey Prof. Paper 318, p. 1-198.
- Wedepohl, K. H., 1963, Beitrage zur Geochemie des Kupfers: Geol. Rdsch., v. 52, p. 492-504.
- West, W. S., and White, M. G., 1952, An occurrence of zuenarite at Brooks Mountain, Seward Peninsula, Alaska: U.S. Geol. Survey Circular 214, p. 1-7.

APPENDIX

Table 1

- Reports published, or committed for publication elsewhere
- Sainsbury, C. L., Helz, Arvin W., Annell, Charles S., and Westley, 1961, Beryllium in stream sediments from the tin-tungsten provinces of the western Seward Peninsula, Alaska: U.S. Geol. Survey Prof. Paper 424-C, p. C16-17.
- Sainsbury, C. L., 1962, A new occurrence of beryllium minerals on the Seward Peninsula, Alaska: U.S. Geol. Survey Open File Report (Preprint of paper delivered at the A.I.M.E. meetings in Anchorage, Alaska, April 17, announcing discovery of the Rapid River deposit).
- Sainsbury, C. L., 1963, Beryllium deposits of the western Seward Peninsula, Alaska: U.S. Geol. Survey Circular 479, p. 1-18.
- Sainsbury, C. L., 1964, Association of beryllium with tin deposits rich in fluorite: Econ. Geology, v. 59, p. 920-929.
- Sainsbury, C. L., 1965, Plane table maps and drill logs of fluorite and beryllium deposits, Lost River area, Alaska: U.S. Geol. Survey Open File Report.
- Sainsbury, C. L., in press, Improved method for studying limestones in thin section: Journal of Sedimentary Petrology.
- Sainsbury, C. L., Quaternary geology of the western Seward Peninsula, Alaska: for inclusion in the Proceedings, VII International Congress of the International Association for Quaternary Research, at Boulder, Colorado, Aug. 30 - Sept. 5, 1965, symposium on the Bering Land Bridge.

Ross, R. J., 1965, Early Ordovician trilobites from the Seward
Peninsula, Alaska: Jour. Paleontology, v. 39, No. 1, p.
17-20.

Table 5a--Quantitative spectrographic analyses of bulk samples of beryllium ores, Lost River area, Alaska ^{1/}

Analyst: Harry Bastron, U. S. Geological Survey

Field No.	Lab No.	Cu	Sn	Pb	Mn	Fe	Cr	V	Ti	Mg	Sr	Ba	B	Be ^{2/}
Rapid River 1	62M-64	.0014	.012	.012	.22	.50	.0018	.0024	.029	.80	.048	.012	1.2	.24
Rapid River 2	62M-65	.0011	.016	.048	.25	.48	.0027	.0020	.030	.90	.050	.012	1.1	.24
Bessie-Mabel	62M-66	.0008	.010	.023	.16	.26	.0002	.0008	.010	.47	.011	.0037	.016	.14
East Lost River 1	62M-67	.0008	.014	.006	.14	.18	.0006	.0020	.019	.38	.034	.0038	.050	.25
East Lost River 2	62M-68	.0022	.033	.004	.12	.80	.0018	.0024	.060	.75	.026	.0060	.032	.15
East Lost River 3	62M-69	.0012	.014	.007	.18	.28	.0013	.0012	.021	1.20	.026	.0035	.039	.17
Camp Creek 1	62M-70	.0006	.009	.007	.20	.25	.0008	.0012	.022	.50	.028	.0055	.42	.25
Camp Creek 2	62M-71	.0011	.010	.037	.16	.41	.0007	.0009	.016	.90	.023	.0060	.75	.11
Camp Creek 3A-1	62M-72	.0010	.015	.008	.11	.37	.0014	.0024	.025	.55	.035	.0060	.16	.20
Camp Creek 3A-2	62M-73	.0012	.014	.008	.25	.38	.0010	.0023	.024	.85	.038	.0050	.16	.24
Camp Creek 3B-2	62M-74	.0007	.012	.006	.18	.34	.0010	.0019	.025	.41	.035	.0085	.34	.26
Camp Creek 3B-1	62M-75	.0009	.016	.006	.14	.40	.0012	.0021	.029	.40	.033	.0080	.19	.26
62-ASn-791	62M-76	.0008	.017	.005	.22	.41	.0010	.0020	.019	.10	.029	.0032	.047	.54
62-ASn-792	62M-77	.0011	.016	.015	.32	.18	.0004	.0014	.014	.49	.032	.0055	.090	.23

Looked for but not found: Ag, Au, Hg, Ru, Rh, Pd, Ir, Pt, Mo, W, Re, Ce, As, Sb, Bi, Te, Zn, Cd, Tl, In, Co, Ni, Ga, Sc, Y, Yb,
La, Zr, Th, Nb, Ta, V, Li, P

The above results have an overall accuracy of ± 15 percent except near limits of detection where only one digit is reported.

^{1/} Figures are in percent of the element listed.

^{2/} Determined fluorimetrically by Ardith Bartel.

Table 9 . Rare element content in weight percent of selected sedimentary and metamorphic rocks

[Analysts: John C. Hamilton, Claude Huffman, Jr., Ardith Bartell, U. S. Geological Survey]

Sedimentary Rocks

Lab. No.	Field No.	Rock type and location	Be	Sn ^{1/}	W	Li	B	Cu ^{2/}	Pb	Zn	Nb
D112973	63-ASn-808	Graywacke, Mint River	0	.0003	B.D.L. ^{4/}	0	.005	.002	.0015	0	.003
D112977	62-ASn-580	Slate, Brooks Mountain	.00015	<.0003	B.D.L.	0	0	.003	.001	0	0
D112979	62-ASn-562	Phyllite, 2 miles north of Brooks Mountain	0	<.0003	B.D.L.	0	0	.003	0	0	0
D112981	62-ASn-890	Argillaceous limestone, west headwaters, Mint River	0	<.0003	B.D.L.	0	.003	.0015	0	0	0
D113006	61-ASn-45A	Silty limestone, Lost River valley	0	<.0003	B.D.L.	0	0	.0005	0	0	0
D113008	61-ASn-1	Argillaceous, carbonaceous limestone, beach 1.5 miles west of Lost River	0	<.0003	B.D.L.	0	0	.0005	0	0	0
D100123	62-ASn-RR23 ^{3/}	Argillaceous limestone, Rapid River									
D113002	62-ASn-629	Slate	.00015	<.0003	B.D.L.	0	0	.01	0	0	0

Metamorphic Rocks

D113978	62-ASn-737A	Hornfels, Brooks Mountain	.001	.0014	B.D.L.	.05	.007	.0005	.005	0	.003
D112980	62-ASn-591	Biotite-andalusite hornfels, near granite, top of Brooks Mountain	.0005	.0025	B.D.L.	0	.07	.0007	.003	0	.003
D113007	61-ASn-120A	Recrystallized argillaceous limestone, Lost River valley	0	<.0003	B.D.L.	0	.003	.0015	0	0	0

^{1/} By ion exchange method, analysts Claude Huffman, Jr., and Ardith Bartel, U. S. Geological Survey.

^{2/} By semiquantitative spectrographic analyses by John C. Hamilton

^{3/} For chemical analysis, see table 3

^{4/} Below detection limit (.01 %)

Detection limits, in percent, as follow: Be, .0001; Sn, .001; W, .01; Li, .02; B, .0001; Pb, .001; Zn, .02; Nb, .001

beryllium deposits, and found no detectable beryllium. Lee

also cautions that most of the allanites reported to contain

FIGURE 42 DISTRIBUTION OF ZONES, MINERALS, AND ELEMENTS IN ZONED
TIN-BERYLLIUM DEPOSITS