GEOLOGICAL SURVEY RESEARCH 1972

Chapter C

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Scientific notes and summaries of investigations
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GEOLOGICAL SURVEY RESEARCH 1972

This collection of 37 short papers is the second published chapter of "Geological Survey Research 1972." The papers report on scientific and economic results of current work by members of the Conservation, Geologic, and Water Resources Divisions of the U.S. Geological Survey.

Chapter A, to be published later in the year, will present a summary of significant results of work done in fiscal year 1972, together with lists of investigations in progress, cooperating agencies, and Geological Survey offices.

"Geological Survey Research 1972" is the thirteenth volume of the annual series Geological Survey Research. The twelve volumes already published are listed below, with their series designations.

Geological Survey Research	*Prof. Paper*
1960	400
1961	424
1962	450
1963	475
1964	501
1965	525
1966	550
1967	575
1968	600
1969	650
1970	700
1971	750

PETROGRAPHIC EVIDENCE OF VOLUME INCREASE RELATED TO SERPENTINIZATION, UNION BAY, ALASKA

By ALLEN L. CLARK and WILLIAM R. GREENWOOD,
Menlo Park, Calif., Jiddah, Saudi Arabia

Work supported in part by National Aeronautics and Space Administration

Abstract.–Petrographic studies of samples from the dunite core of the ultramafic complex at Union Bay in southeastern Alaska reveal several features that indicate volume expansion was associated with serpentinization. These features include kink bands offset along transecting serpentine veinlets, rotated fragments of larger olivine grains enclosed by serpentine, expanded chromite grains cut by serpentine-filled fractures, and radially fractured diopside grains adjacent to preferentially serpentinized olivine grains.

The question of which remains constant during serpentinization of ultramafic rocks–volume or composition–has been debated by Turner and Verhoogen (1960, p. 316–321) and Thayer (1966), who believe that serpentinization is an equal volume process accompanied by the loss of MgO and SiO_2, and by Shteinberg (1960), Hess and Otalora (1964), Green (1964), and Hostetler and others (1966), who contend that serpentinization involves volume increase with constant composition except for hydration. Beeson and Jackson (1969) maintain that under certain conditions both volume and composition may remain constant. This paper presents petrographic evidence that has a bearing on the problem.

GENERAL GEOLOGY

The ultramafic complex at Union Bay, southeastern Alaska, approximately 35 miles north-northwest of Ketchikan, is one of 35 or more ultramafic bodies that crop out along the 350-mile-long Alaskan panhandle (fig. 1) (See Clark and Greenwood, 1972, p. C157–C160, this chapter).

Previous studies on the complex at Union Bay resulted in a number of brief descriptions by Buddington and Chapin (1929), Kennedy and Walton (1946), and Walton (1951), and a detailed report by Ruckmick and Noble (1959). A review of the zoned ultramafic occurrences of southeastern Alaska by Taylor (1967) includes a sketch map and a brief description of the complex at Union Bay.

Ruckmick and Noble (1959, p. 981) describe the complex as follows:

> A body of gabbro, approximately circular in plan and about 6 miles in diameter, intrudes folded sedimentary rocks of probably Triassic and Cretaceous age. A moderately low grade of regional metamorphism in the sedimentary rocks is increased to almandite-zone grade adjacent to the gabbroic contact. Intrusive into the gabbro is a remarkable ultramafic complex which comprises a vertical pipe approximately 1 mile in diameter, to which is attached a lopolithic offshoot approximately 5 miles long and 3 miles wide. The ultramafic units range through hornblende pyroxenite, pyroxenite, olivine pyroxenite, periodotite, and dunite, and both the pipe and the lopolith show a well-developed concentric zoning with dunite in the center and pyroxenite or hornblende pyroxenite on the periphery. Magnetite is a primary constituent of the pyroxenite unit.

The present study focused on the dunite core, which is exposed over an area of approximately 1 square mile in the eastern part of the complex (fig. 2).

Extrapolated from unaltered parts, the primary original composition of dunite from the core was 95 to 98 percent olivine in an equigranular aggregate of equant to subhedral grains. Ruckmick and Noble (1959, p. 1003) report a narrow range of composition from Fo_{90} to Fo_{93}. Most of the olivine grains show a wavy or undulatory extinction, and indication of strain. The olivine is commonly "kink" banded, indicating inhomogeneous translation gliding (Orowan, 1942; Hess and Barrett, 1949).

Diopside constitutes the remaining 2 to 5 percent of the unaltered dunite from the core; it occurs primarily as scattered anhedral grains interstitial to the olivine.

The dunite core is locally strongly serpentinized. According to Ruckmick and Noble (1959, p. 1003), "In a typical specimen of partially serpentinized dunite, only 5–10 percent of the olivine has been altered to bowlingite, antigorite, chrysotile and secondary magnetite along fractures." During the present study, mineral separates from the serpentinized dunite were studied by X-ray diffraction techniques described

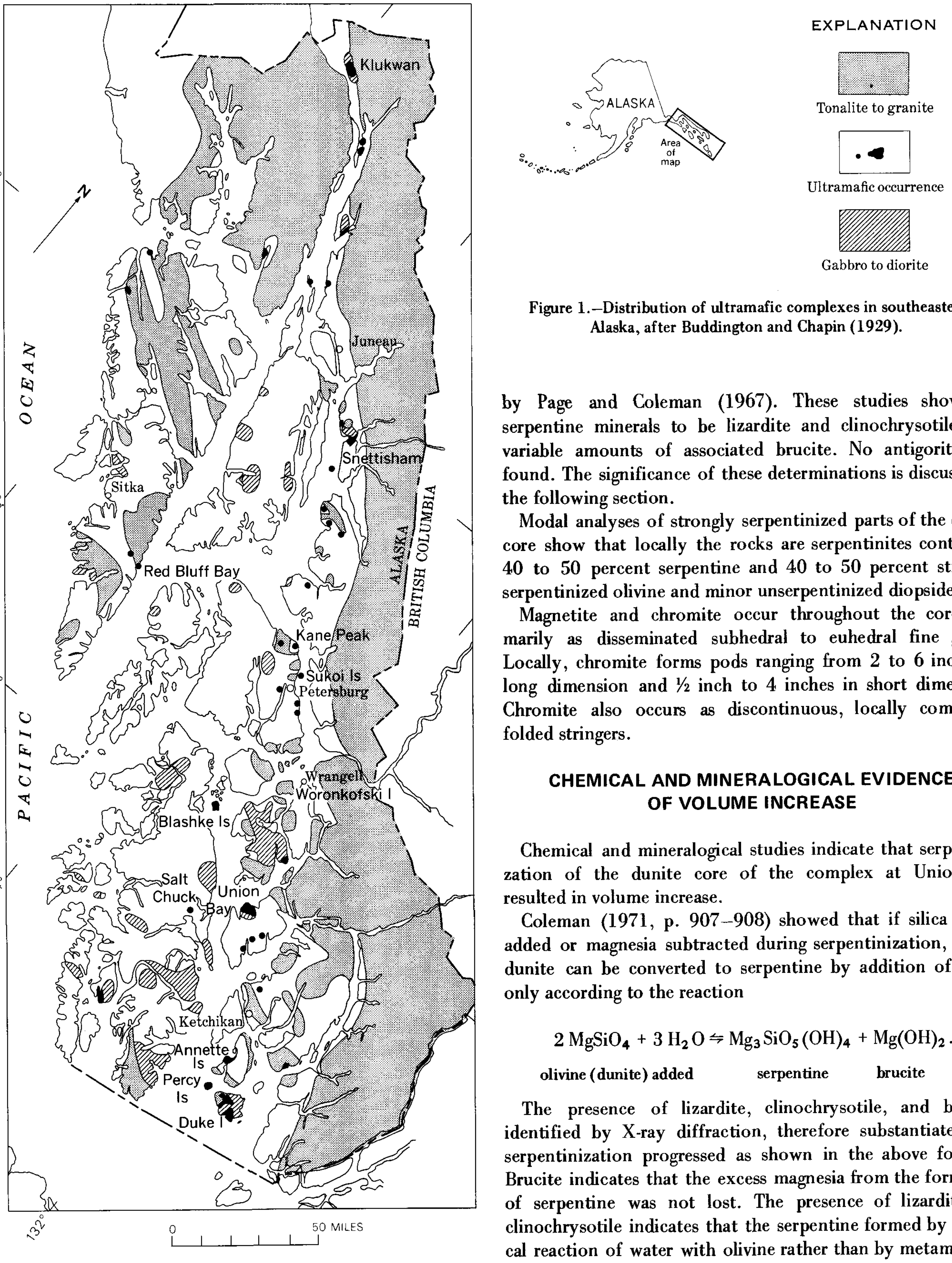

Figure 1.—Distribution of ultramafic complexes in southeastern Alaska, after Buddington and Chapin (1929).

by Page and Coleman (1967). These studies show the serpentine minerals to be lizardite and clinochrysotile with variable amounts of associated brucite. No antigorite was found. The significance of these determinations is discussed in the following section.

Modal analyses of strongly serpentinized parts of the dunite core show that locally the rocks are serpentinites containing 40 to 50 percent serpentine and 40 to 50 percent strongly serpentinized olivine and minor unserpentinized diopside.

Magnetite and chromite occur throughout the core, primarily as disseminated subhedral to euhedral fine grains. Locally, chromite forms pods ranging from 2 to 6 inches in long dimension and ½ inch to 4 inches in short dimension. Chromite also occurs as discontinuous, locally complexly folded stringers.

CHEMICAL AND MINERALOGICAL EVIDENCE OF VOLUME INCREASE

Chemical and mineralogical studies indicate that serpentinization of the dunite core of the complex at Union Bay resulted in volume increase.

Coleman (1971, p. 907–908) showed that if silica is not added or magnesia subtracted during serpentinization, then a dunite can be converted to serpentine by addition of water only according to the reaction

$$\underset{\text{olivine (dunite)}}{2\,\mathrm{MgSiO_4}} + \underset{\text{added}}{3\,\mathrm{H_2O}} \rightleftharpoons \underset{\text{serpentine}}{\mathrm{Mg_3SiO_5(OH)_4}} + \underset{\text{brucite}}{\mathrm{Mg(OH)_2}}.$$

The presence of lizardite, clinochrysotile, and brucite, identified by X-ray diffraction, therefore substantiates that serpentinization progressed as shown in the above formula. Brucite indicates that the excess magnesia from the formation of serpentine was not lost. The presence of lizardite and clinochrysotile indicates that the serpentine formed by chemical reaction of water with olivine rather than by metamorphic

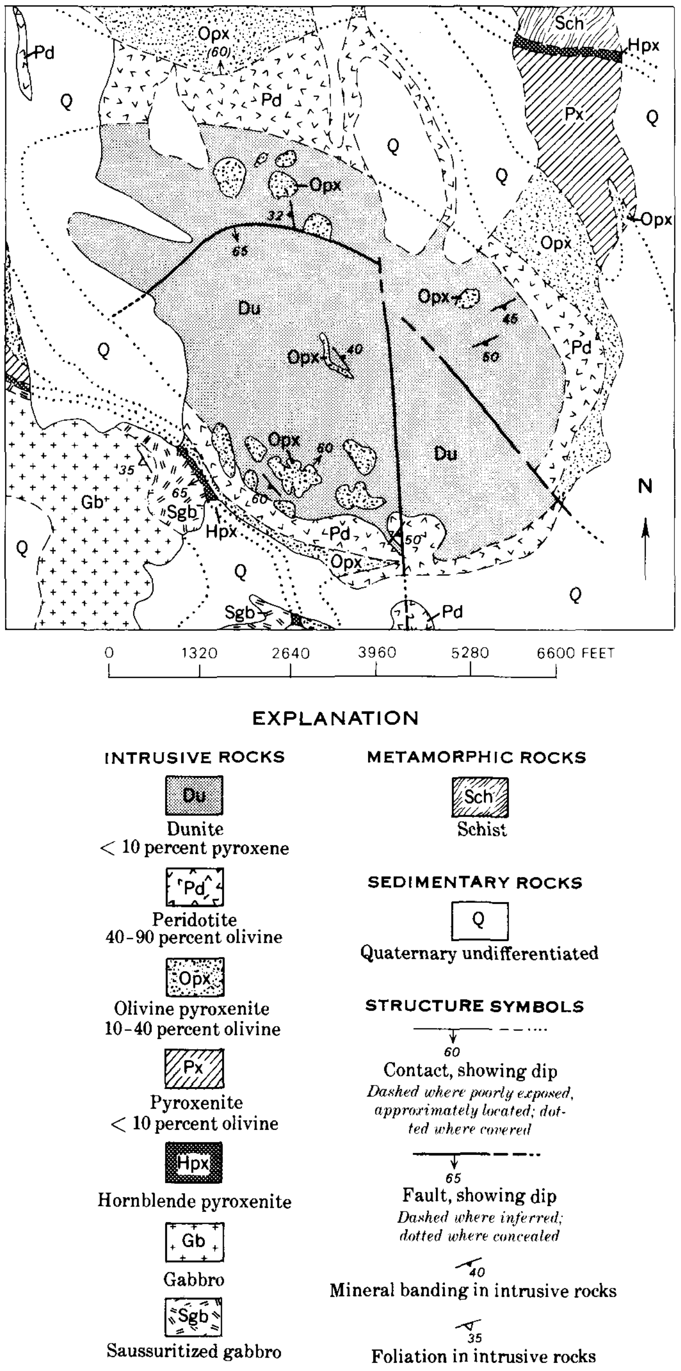

Figure 2.—Geologic map of the dunite core and other rocks, ultramafic complex at Union Bay, southeastern Alaska. Modified from Ruckmick and Noble (1959).

processes that would be expected to yield antigorite (Coleman, 1971, p. 906–907).

According to Coleman (1971, p. 908), "The average MgO/SiO_2 ratio for dunites is ≈ 1.23 and if serpentinization of a dunite is accomplished only by addition of water, this ratio should remain constant." For the brucite-bearing massive serpentinite derived from dunites, the MgO/SiO_2 value has been found to be ≈ 1.23 (Thompson, 1968; Coleman and Keith, 1972). Calculated MgO/SiO_2 values for serpentinized and unserpentinized dunites from the dunite core (Ruckmick and Noble, 1959, p. 984–985, table 1, samples 183a and 231) and analyses by the authors yield a range of 1.18 to 1.24. Samples studied contained from 0 to 35 percent modal serpentine. The mineralogy, that is, the presence of lizardite, clinochrysotile, and brucite, and the chemistry as represented by MgO/SiO_2 values ≈ 1.23, clearly demonstrate that serpentinization of the dunite core involved only the addition of water.

Because serpentine minerals contain from 12 to 13.5 weight percent water, there must be resultant increase in volume related to the formation of serpentine.

Volume-factor analyses (fv) following the equation developed by Gresens (1967) yield values of $fv = 1.196$ and $fv = 1.165$ based on samples that contain 0 to 10 percent modal serpentine, with specific gravities of 3.3 and 2.85, respectively, and MgO/SiO_2 values for the dunite of 1.19 and for the resultant serpentinite of 1.22. These values are taken to represent average serpentinized dunite of the core and show that volume expansion of 16 to 20 percent must have taken place to maintain the same MgO/SiO_2 values in the serpentinite as in the dunite.

The data therefore show that the dunite core has undergone volume expansion of 16 to 20 percent resulting from the addition of water and the resultant formation of serpentine without addition of silica or removal of magnesia.

PETROGRAPHIC EVIDENCE RELATING TO THE PROBLEM OF VOLUME INCREASE DURING SERPENTINIZATION

The proponents of volume expansion during serpentinization have suggested various amounts of expansion. Hess (1955, p. 403) suggested a 25-percent increase in volume in serpentinized dunites; Hostetler and others (1966) argued that a volume increase of 35 to 40 percent is probably common in rocks that originally contained only pyroxene, and Engin and Hirst (1970, p. 292) calculated a volume increase of 39 percent in the harzburgites of the Andrezlik-Zimparalik peridotite body of Turkey. Thayer (1966, p. 695) calculated that volume increases of 35 to 40 percent, the general range proposed by other workers, would result in an equivalent linear expansion of 11 to 12 percent and should be readily detectable in rocks under suitable conditions.

The dunite core of the ultramafic complex at Union Bay is locally strongly sheared and serpentinized (fig. 3). Thin-section studies reveal an apparent disruption of internal features: kink bands are offset along transecting serpentine veinlets, rotated fragments of larger olivine grains are enclosed by serpentine, expanded chromite grains are cut by serpentine-filled fractures, and radially fractured diopside grains are adjacent to preferentially serpentinized olivine grains related to volume

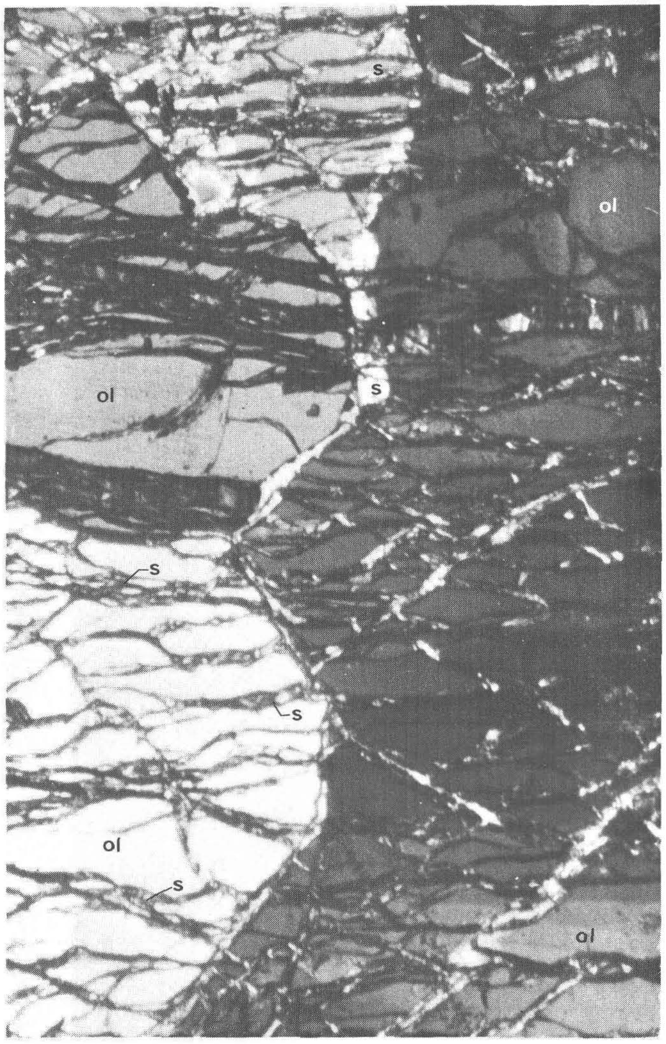

Figure 3.—Strongly sheared and serpentinized dunite. Serpentine veinlets form complex anastomosing network. ol, olivine; s, serpentine.

increase of approximately the amount (16–20 percent) calculated.

Offset of kink bands

Olivine grains in the dunite core characteristically have well-developed kink bands (figs. 4 and 5). The general nature and origin of such kink bands are duscussed by Raleigh (1968). Those in the ultramafic complex at Union Bay are being studied by W. R. Greenwood and others in work in progress.

At Union Bay, serpentine veinlets that crosscut kink bands in the olivine characteristically displace the bands. The significance of this displacement was discussed by Raleigh 1963, p. 63), who stated:

> Exsolution lamellae of clinopyroxene, which persist through serpentinized parts of the grains, are offset by zones of serpentine which intersect the lamellae at angles of less than 90 degrees. The offsets in every case are in the sense which would be produced by expansion in the serpentine band normal to its boundaries. In the same grains, the traces of lamellae are not offset by zones of serpentine trending perpendicular to the lamellae. The lamellae within the serpentinized zone are commonly pulled apart slightly along their length. These relationships can only be explained by expansion within the zone of serpentine approximately normal to its boundaries***.
>
> The boundaries of extinction bands in olivine grains are also offset in the proper sense (like offsets on reverse faults) where they are intersected at less than 90 degrees by bands of serpentine.

Figure 4 shows serpentine veinlets that cut nearly at right angles across the kink bands with no apparent offset of the bands of the individual parts of the olivine grain. Figure 5 shows a veinlet transecting a kink band at an oblique angle, causing a lateral shift in the band.

Figure 5 clearly indicates that linear expansion associated with volume increase during the development of the crosscutting serpentine veinlets has resulted in offset of the kink bands. The authors are aware that shearing and fine-scale fractures and faults could cause the features observed. How-

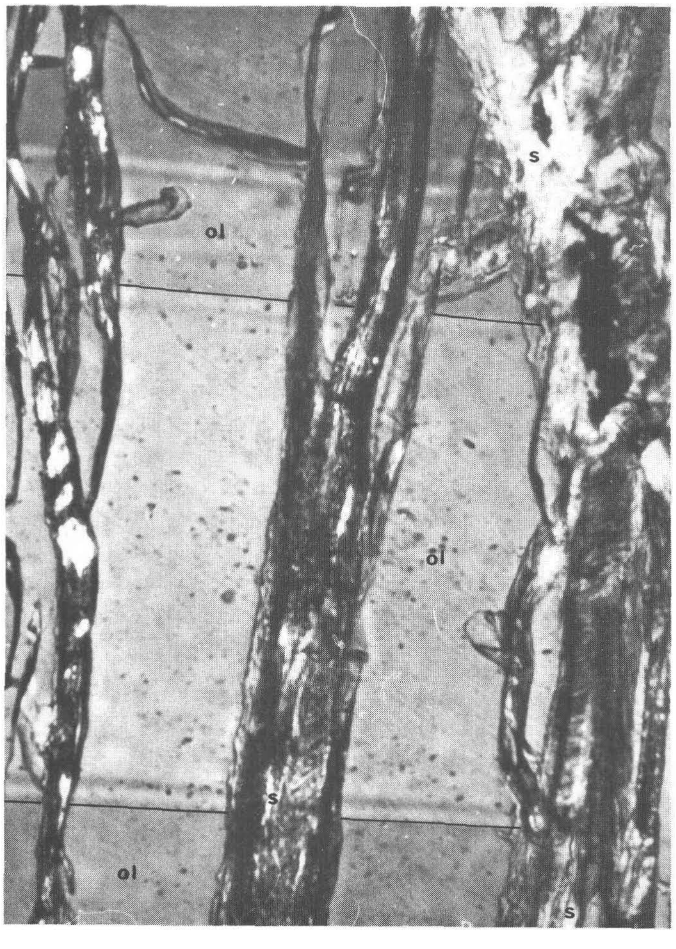

Figure 4.—Strongly kink banded olivine grain, with kinks developed parallel to (100) cut by serpentine veinlets. ol, olivine; s, serpentine.

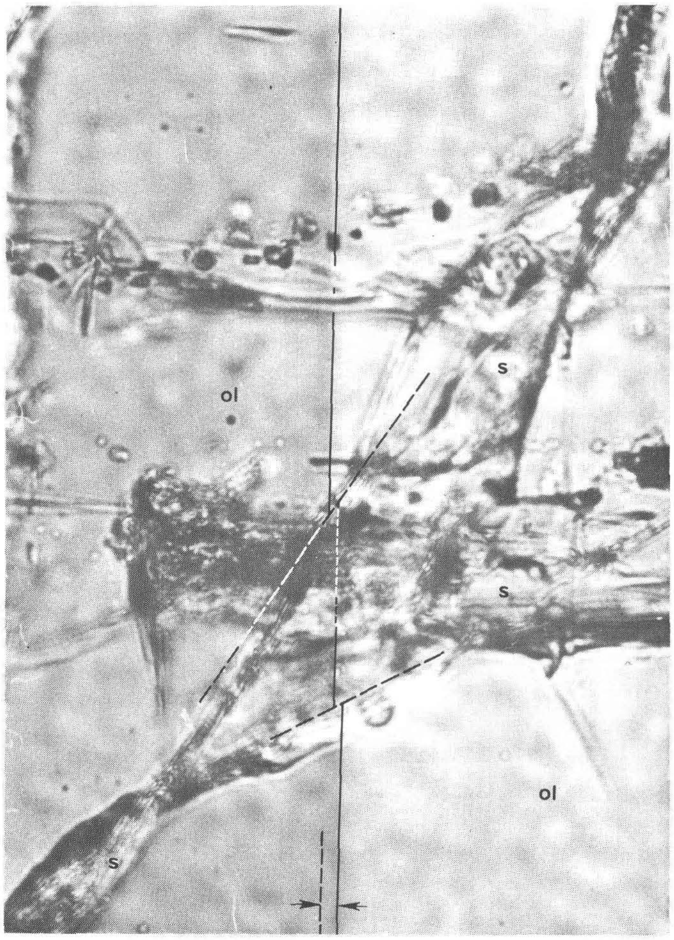

Figure 5.–Olivine grain with kink band parallel to (100) offset by serpentine veinlet (dashed lines) crossing kink band at oblique angle. Arrows show total offset. ol, olivine; s, serpentine.

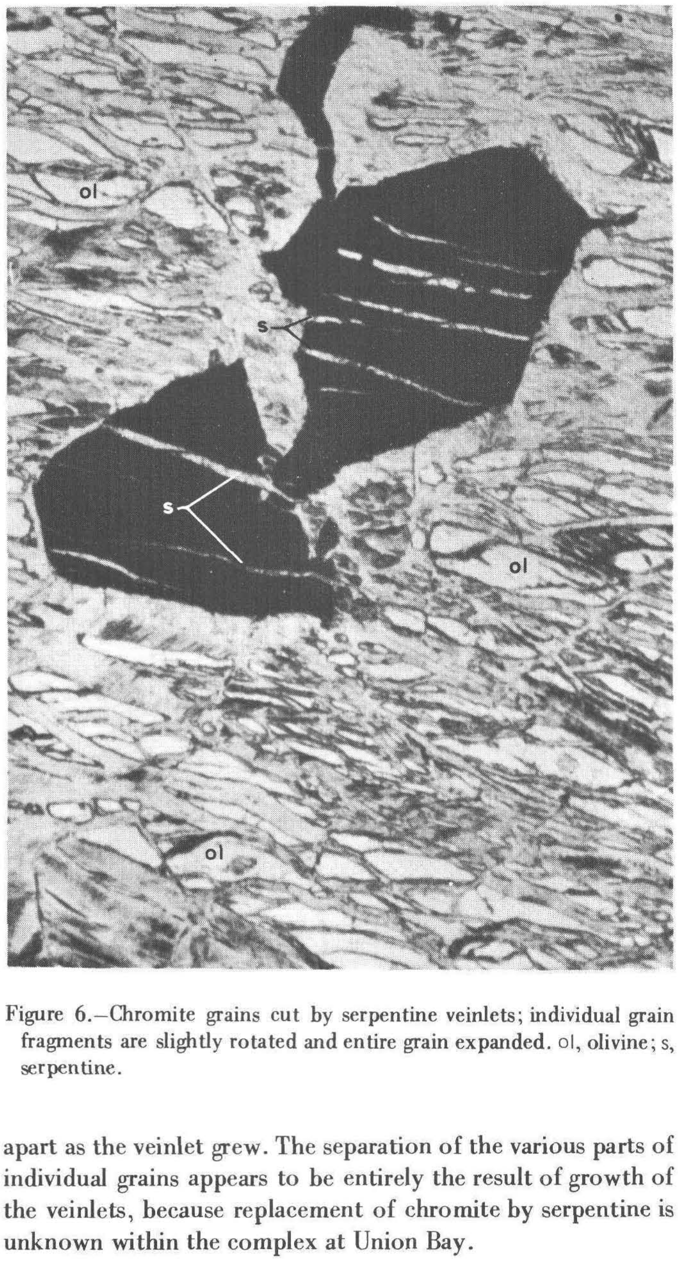

Figure 6.–Chromite grains cut by serpentine veinlets; individual grain fragments are slightly rotated and entire grain expanded. ol, olivine; s, serpentine.

ever, the parallelism across serpentine veinlets that cross the kink bands at 90 degrees and the offset along serpentine veinlets that cross at an acute angle strongly suggest that the serpentine veinlets caused the internal disruptions. It is also conceivable that minor shearing and fracturing may accompany the volume increase, resulting in rotation and disruption of individual isolated parts of the same olivine grains. In addition, it will be shown later that calculated offsets are of the magnitude expected, if they are the result of volume expansion during serpentinization.

Volume expansion of chromite grains

Euhedral to subhedral grains of chromite and magnetite are common within the dunite of the ultramafic complex at Union Bay. Many are cut by veinlets of serpentine and appear to have undergone volume expansion related to the growth of the veinlets (figs. 6 and 7).

In most of the chromite grains, the walls on either side of the serpentine veinlets are matched, so the grain simply spread apart as the veinlet grew. The separation of the various parts of individual grains appears to be entirely the result of growth of the veinlets, because replacement of chromite by serpentine is unknown within the complex at Union Bay.

Volume expansion associated with preferential serpentinization of olivine

Within the dunite core, olivine grains normally are preferentially serpentinized with respect to adjacent grains of diopside. At the contact of the grains of olivine and diopside, a radial fracture pattern is developed in the diopside. Ruckmick and Noble noted that the same phenomenon developed where interstitial areas of diopside enclose partly serpentinized grains of olivine (1959, p. 1001, pl. 3, fig. 3).

Similar radial structures have been described in feldspars surrounding serpentinized olivine grains and considered as strong evidence of volume increase during serpentinization (Smith, 1958). On a larger scale, Mossman (1970, p. 3756)

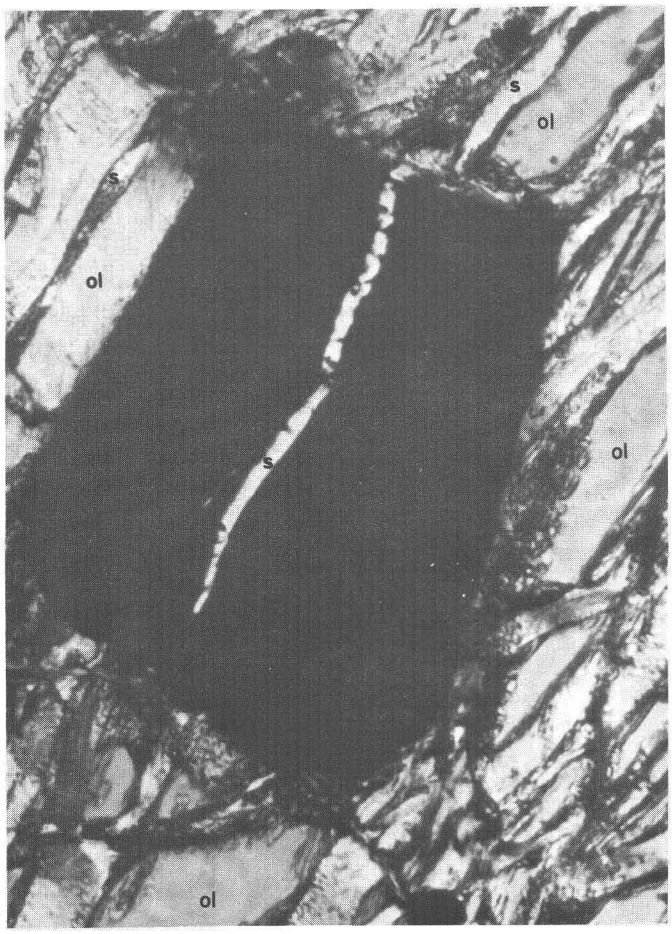

Figure 7.—Chromite grain cut by serpentine veinlet. Note matching opposed walls along veinlet indicating separation and expansion of grain. ol, olivine; s, serpentine.

described similar radial structures associated with serpentinized dunite blocks in wehrlite. A similar phenomenon was described by Ruckmick and Noble (1959, p. 1001), who stated:

> In many places in the structural peridotite where dunitic material exhibits a rounded, convex contact against the olivine pyroxenite, radial fracture patterns occur in pyroxene-rich rock adjacent to the contact. This feature is especially obvious where small bodies of dunitic rock show a circular cross section. The nature of this secondary (post-solidification) fracture pattern indicates either that the olivine has increased in volume or that the pyroxene has decreased in volume. Because the coefficient of expansion with temperature is greater for olivine than for diopside ***, the fractures were probably not caused by differential contraction as the intrusion cooled. All the dunitic rocks associated with this feature contain approximately 10 percent or more of serpentine minerals, and possibly the fractures were caused by relative expansion of the dunitic material during serpentinization of the olivine.

Ruckmick and Noble's contention that the fractures were not produced as the intrusion cooled is substantiated by the absence of high-temperature antigorite and the presence of low-temperature lizardite and clinochrysotile (Coleman, 1971, p. 901).

It is especially noteworthy that within the complex at Union Bay, volume expansion associated with preferential serpentinization occurs at both microscopic and macroscopic scales, which supports Thayer's contention (1966, p. 696) that major disruptions should be associated with serpentinization.

CALCULATIONS OF LINEAR EXPANSION ASSOCIATED WITH VOLUME INCREASE

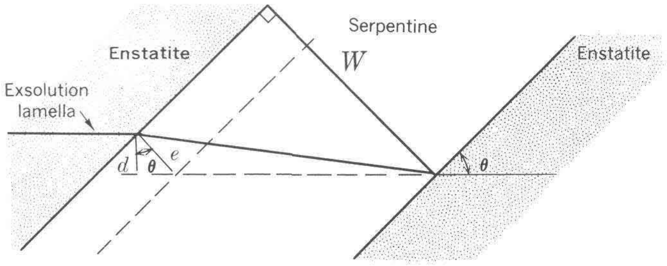

Figure 8.—Diagram showing offset, *d*, of exsolution lamella by expansion of amount, *e*, in band of serpentine (of width *W*) transecting a grain of enstatite (after Raleigh, 1963, p. 65–66).

Detailed measurements on individual olivine grains, showing offset of kink bands along serpentine veinlets, were made using the technique described by Raleigh (1963, p. 63–69). (See figure 8.) According to Raleigh, the volume increase in the bands of serpentine can be calculated by assuming that expansion took place only in a direction normal to the boundaries of the bands. This assumption is verified by observations on lamellae that persist through bands of serpentine lying normal to the lamellae; the lamellae within the bands show no displacement parallel to the margins of the band. Referring to figure 8, the linear expansion, e, normal to the boundary is given by

$$e = \frac{d}{\cos\theta}$$

where d is the amount of offset of the lamella and θ is the acute angle between the lamella and the boundary of the band. The fraction of volume increase, $\frac{\Delta V}{V}$, is then

$$\frac{\Delta V}{V} = \frac{e}{W - e},$$

where W is the thickness of the band.

Six grains were studied and $\frac{\Delta V}{V}$ calculated for each. The values calculated ranged from 10 to 34 percent and averaged 22 percent. The range is attributable to variations in amount of modal serpentine, 5 to 18 percent, and difficulty in accurately measuring the band widths.

Volume expansion of chromite grains was measured by enlarging photographs of serpentine-bearing chromite grains, computing the present volume, then cutting out the serpentine veinlets from the photographs, fitting the grains back to their original configuration, and recalculating the volume. The difference between the two volume calculations then represented the volume increase, which ranged from 8 to 29 percent for the four grains measured. The wide range probability stems from our inability to make a three-dimensional calculation on an individual grain.

Although the range in percentage of volume increase calculated by these methods is fairly large, the averages are very close to the 16 to 20 percent calculated by Gresens' (1967) technique.

CONCLUSIONS

Mineralogical and chemical studies of dunite samples from the core of the ultramafic complex at Union Bay show that serpentinization took place without addition of silica or removal of magnesia. The volume increase to be expected was calculated as ranging from 16 to 20 percent. Measurements of the actual amount of volume increase associated with offset kink bands and serpentinization of individual chromite grains are approximately the same as the theoretically calculated amounts.

Petrographic studies show that serpentinization of the dunite core of the complex at Union Bay caused internal disruption of structural elements. Kink bands are offset by transecting veinlets of serpentine, chromite grains have expanded owing to development of serpentine veinlets, and differential serpentinization of olivine grains has produced radial fractures in adjacent diopside grains. Both the small- and large-scale structural disruptions are best explained by volume increase during serpentinization of the dunite core.

The mineralogical, chemical, and petrographic studies show that serpentinization of the dunite core was a constant-composition process resulting in volume increase of approximately 16 to 20 percent.

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THRUST FAULTS, ANNETTE-GRAVINA AREA, SOUTHEASTERN ALASKA

By HENRY C. BERG, Menlo Park, Calif.

Abstract.—Thrust faults recently mapped on Annette and Gravina Islands, near Ketchikan, represent the first documented large-scale thrusting in southeastern Alaska. The thrusts displace bedded rocks as young as late Mesozoic and are offset by high-angle faults, probably mainly of middle Tertiary age. The largest zone of thrusting, on western Annette Island, juxtaposes geologically and physiographically dissimilar terranes, truncating a metamorphic aureole on one terrane by at least 5 miles. A thrust on southern Gravina Island emplaces slightly deformed Paleozoic rocks over intensely deformed Mesozoic rocks; its net slip may be as much as a mile. In places, intersections of this thrust with high-angle faults are marked by zones of hydrothermally altered rocks containing sparse copper minerals and barite. Large-scale thrust faults now are being recognized in many other places in southeastern Alaska. This recognition is leading to reinterpretations of the region's structural and tectonic history that favor mobilistic hypotheses of major tectonic dislocation and continental fragmentation.

The first low-angle thrust faults with large displacements to be documented in southeastern Alaska have been mapped on Annette and Gravina Islands (herein also called Annette-Gravina area) near Ketchikan (fig. 1). The main thrusts are, by their gentle dips and net slips of a mile or more, distinct from the numerous high-angle reverse faults and from the few other, less well-documented thrust faults mapped elsewhere in southeastern Alaska (Lathram and others, 1959, 1965; Loney and others, 1963a, b; Loney, 1964; Muffler, 1967). The thrusts are offset by presumably younger high-angle normal and strike-slip faults.

The thrusts originated in a Late Jurassic—middle Tertiary interval. In the Annette-Gravina area, they displace rocks as young as Late Jurassic and are cut by high-angle faults that are inferred correlatives of middle Tertiary faults known elsewhere in southeastern Alaska (Ovenshine and Brew, 1972). A more definitive interval of post-Early Cretaceous—pre-middle Tertiary time is suggested by recent mapping on Etolin Island, 65 miles northwest of Ketchikan, where beds as young as Albian probably were involved in the deformation that produced the thrusting in the Annette-Gravina area (Berg, unpub. data).

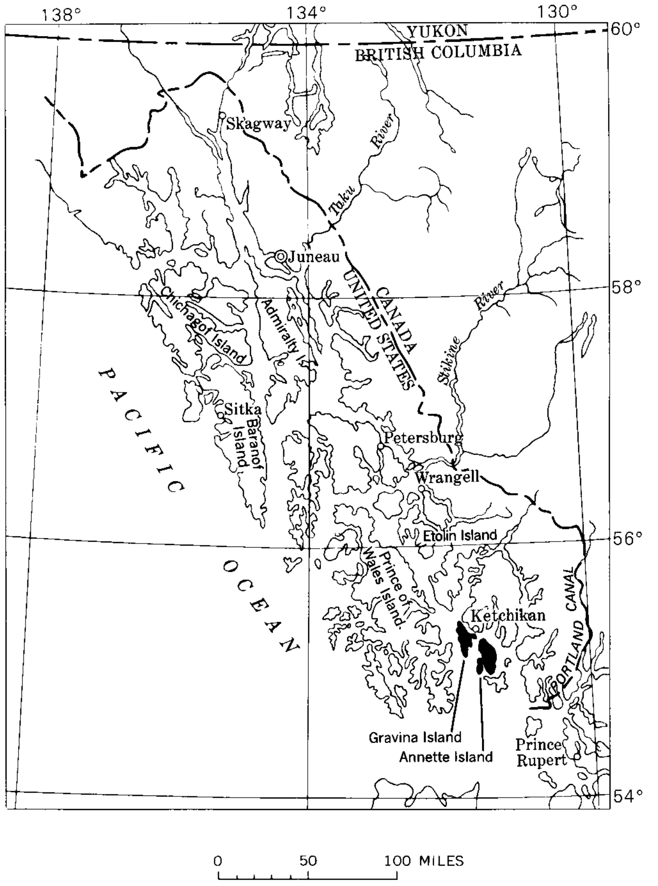

Figure 1.—Index map of southeastern Alaska, showing location of Annette and Gravina Islands.

ANNETTE ISLAND

Several thrust faults, including a main thrust zone with an estimated minimum net slip of 5 miles, occur on Annette Island, about 20 miles south of Ketchikan (fig. 2). The first such large-scale thrust mapped in southeastern Alaska, the main zone was first inferred from the occurrence of deep, water-bearing, permeable zones on Metlakatla Peninsula (Marcher, 1969), then documented by detailed geologic mapping (Berg, 1970, 1972; U.S. Geol. Survey, 1970). In addition to the main zone on western Annette Island, several other thrust faults have been mapped; their magnitude and

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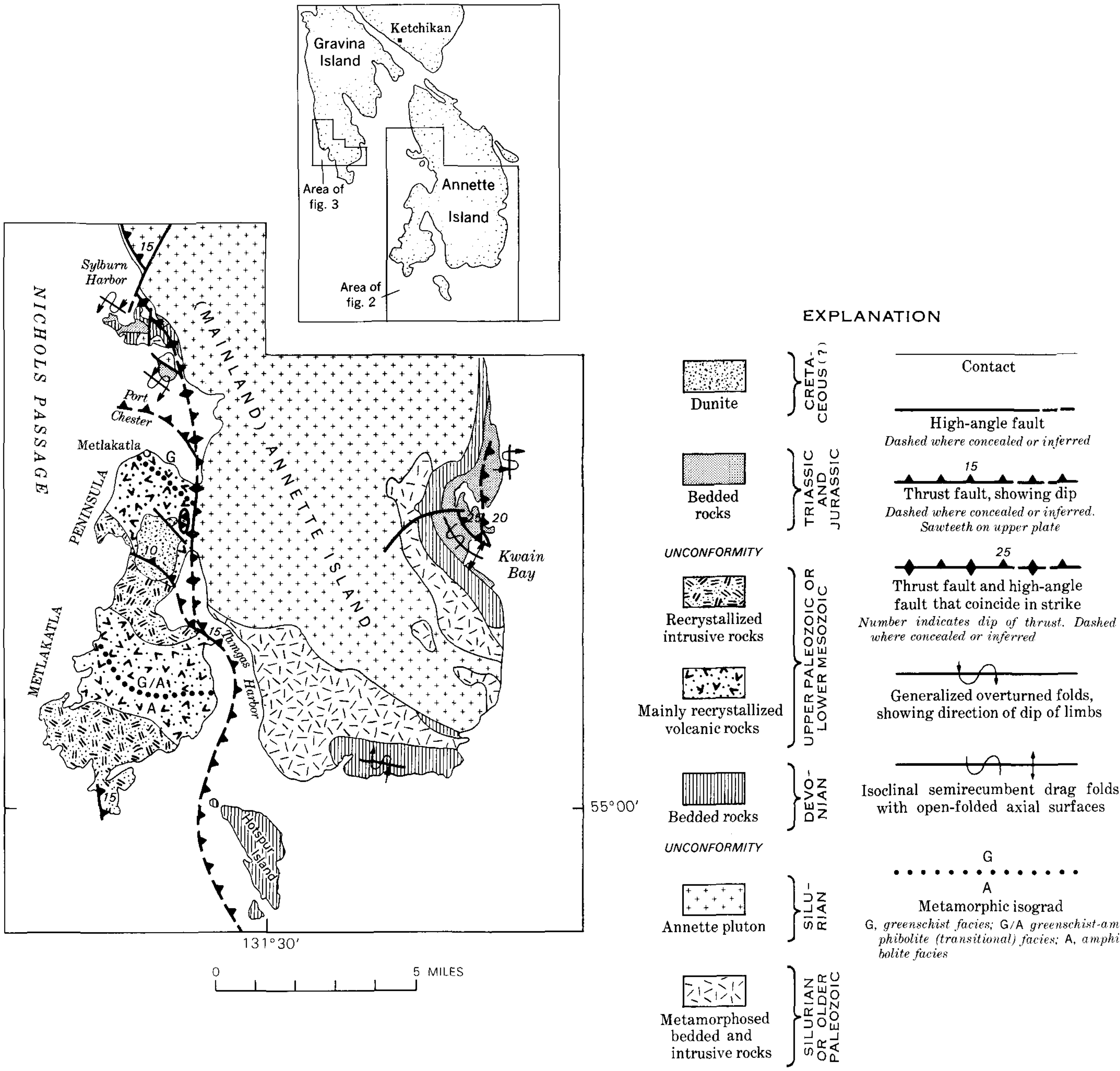

Figure 2.—Generalized geologic map of part of Annette Island, Alaska.

extent are less well known. All of the thrusts are disrupted by high-angle faults that in some places offset them and in others coincide with their strike (fig. 2).

Annette Island consists of two geologically distinct terranes that differ markedly in physiography, lithology, and type and grade of metamorphism (Berg, 1972)—mainland Annette Island and Metlakatla Peninsula, a large southwestern appendage of the island. Hotspur Island, just off the south coast of Annette Island, is included in the mainland Annette terrane.

Mainland Annette is mountainous (maximum elevation, 3,591 feet) and is underlain by a diverse suite of bedded and intrusive rocks ranging in age from Silurian or older Paleozoic to Middle or Late Jurassic. Except for the Annette pluton, whose core is brecciated but not schistose, the rocks commonly are foliated and characterized by greenschist facies and lower grade regional metamorphism.

Metlakatla Peninsula, a muskeg-covered lowland (maximum elevation, 540 feet), is underlain mostly by recrystallized volcanic and intrusive rocks of indefinite, but probably mainly late Paleozoic or early Mesozoic, age (Berg, 1972; revised in Berg, 1973) and by a small dunite body of Cretaceous(?) age. Most of the rocks are phyllitic to gneissic, but many lack pronounced foliation. Metamorphism grades from greenschist facies on the north to amphibolite facies on the south.

The main thrust zone is a complex network of low- and high-angle faults that mainly separates Metlakatla Peninsula from the rest of Annette Island. In general, it strikes sinuously northward and dips eastward at an angle of 15° or less. Several strands that strike westward dip gently northward. Where the low-dipping faults coincide in strike with high-angle faults, the thrust surfaces commonly are rotated and dragged into much steeper attitudes and therefore are difficult to distinguish from the normally steep high-angle faults. Bedrock along the trace of the main zone, which in places may be as much as a mile wide, is intensely sheared, with numerous closely spaced graphitic and micaceous slip surfaces. Typically, the shear zones contain ellipsoidal blocks of relatively unsheared rock several tens of feet in maximum dimension. Differential erosion of the sheared rocks in the main zone has produced the three harbors on western Annette Island—Sylburn Harbor, Port Chester, and Tamgas Harbor. It is possible, in fact, that the flat, low-lying Metlakatla Peninsula was formed by a combination of glacial and marine planation along low-dipping shear surfaces contiguous to the main thrust zone.

The estimated net slip of the main thrust zone is based on the truncation of a metamorphic aureole on Metlakatla Peninsula. The aureole, produced by metamorphism that postdates a late Paleozoic or early Mesozoic pluton on the south end of the peninsula, grades from amphibolite facies on the south to biotite (and locally chlorite) zone greenschist facies on the north (fig. 2), indicating a width of at least 6 miles. The aureole has not been recognized in the Devonian and older Paleozoic rocks on mainland Annette Island and Hotspur Island. The metamorphic isograds trend west to northwest and terminate abruptly on the east against chlorite-zone greenschist facies rocks on mainland Annette and still lower grade (prehnite-pumpellyite metagraywacke facies?) rocks on Hotspur Island. That none of these older rocks were affected by the metamorphism on Metlakatla Peninsula indicates that they were beyond the 6-mile aureole at the time of that metamorphism. The present one-mile minimum between amphibolite on southern Metlakatla Peninsula and the low-grade rocks on Hotspur Island suggests a displacement of at least 5 miles on the main thrust zone.

Two other conspicuous thrust faults on Annette Island are exposed in the Kwain Bay area (fig. 2). The bedded rocks near these gently eastward dipping faults are intensely deformed, presumably largely by drag in conjunction with the thrusting, but the net slip cannot be measured because the thrusts juxtapose rocks of roughly the same age and lithology. The complex structures in the bedded rocks, which include isoclinal recumbent folds with warped axial surfaces, suggest that the cumulative displacement on these thrusts may be appreciable.

SOUTHERN GRAVINA ISLAND

A major thrust fault, indicated by anomalous stratigraphy and structure, is exposed over a 10-square-mile area near the south end of Gravina Island (fig. 3). This fault, which dips gently northward, thrusts slightly deformed Paleozoic rocks over intensely deformed Mesozoic rocks and is offset by high-angle faults.

The bedded rocks on southern Gravina Island comprise three unconformable sequences. The oldest consists of diverse greenschist-to-amphibolite facies metamorphosed bedded and intrusive rocks. It is assigned an age of Silurian or older Paleozoic because it is intruded by apophyses of the Annette pluton, a radiometrically dated Silurian stock that crops out mainly on Annette Island (Berg, 1972, 1973). The next younger sequence comprises weakly metamorphosed volcanic and sedimentary rocks. Its assigned age, based on scant, poorly preserved upper Silurian(?) and Devonian(?) fossils in the sedimentary rocks, is middle Paleozoic. The most significant unit in this sequence is the Puppets Formation (Berg, 1973), a conspicuous 400-foot-thick unit of metarhyolite whose anomalous outcrop pattern first led to the recognition of thrusting on southern Gravina Island. The youngest sequence includes sedimentary and mafic volcanic rocks, generally only slightly deformed and recrystallized, whose age, based on locally abundant fossils, ranges from Late Triassic to Late Jurassic.

The best exposures of the thrust fault are at Nehenta Bay, where horizontal and gently dipping metarhyolite of the Puppets Formation overlies complexly deformed Upper Triassic slate, limestone, and conglomerate. The contact is exposed on the north shore of the bay, where it dips gently to moderately northeastward. It ranges from a sharply delineated single surface with little gouge to a zone perhaps several tens of feet thick containing slices of country rock separated by graphite- and mica-coated slip surfaces. In other parts of the Nehenta Bay area, intersections of this fault with high-angle faults are marked by zones of intensely hydrothermally altered rocks that contain sporadically distributed copper minerals and barite.

The complex structures in the Triassic beds below the thrust include composite small folds and intersecting lineations and are attributed mainly to drag associated with the thrusting. Except for coastal exposures, mapping of these lower-plate rocks is hindered by poor outcrops and limited areal extent, but the available evidence suggests that the intensity of the deformation diminishes with increasing distance from the thrust.

The only other place where a thrust fault intersects the coastline of southern Gravina Island, and is thus fairly well exposed, is about 3½ miles north of Nehenta Bay. Although the fault there dips gently northeastward, it juxtaposes rocks of roughly the same age and lithology and can only be inferred to correlate with the main thrust at Nehenta Bay.

On the heavily forested ridges northeast of Nehenta Bay, the trace of the thrust is marked by an apparently intermittent, gently northward-dipping zone of intense brecciation and

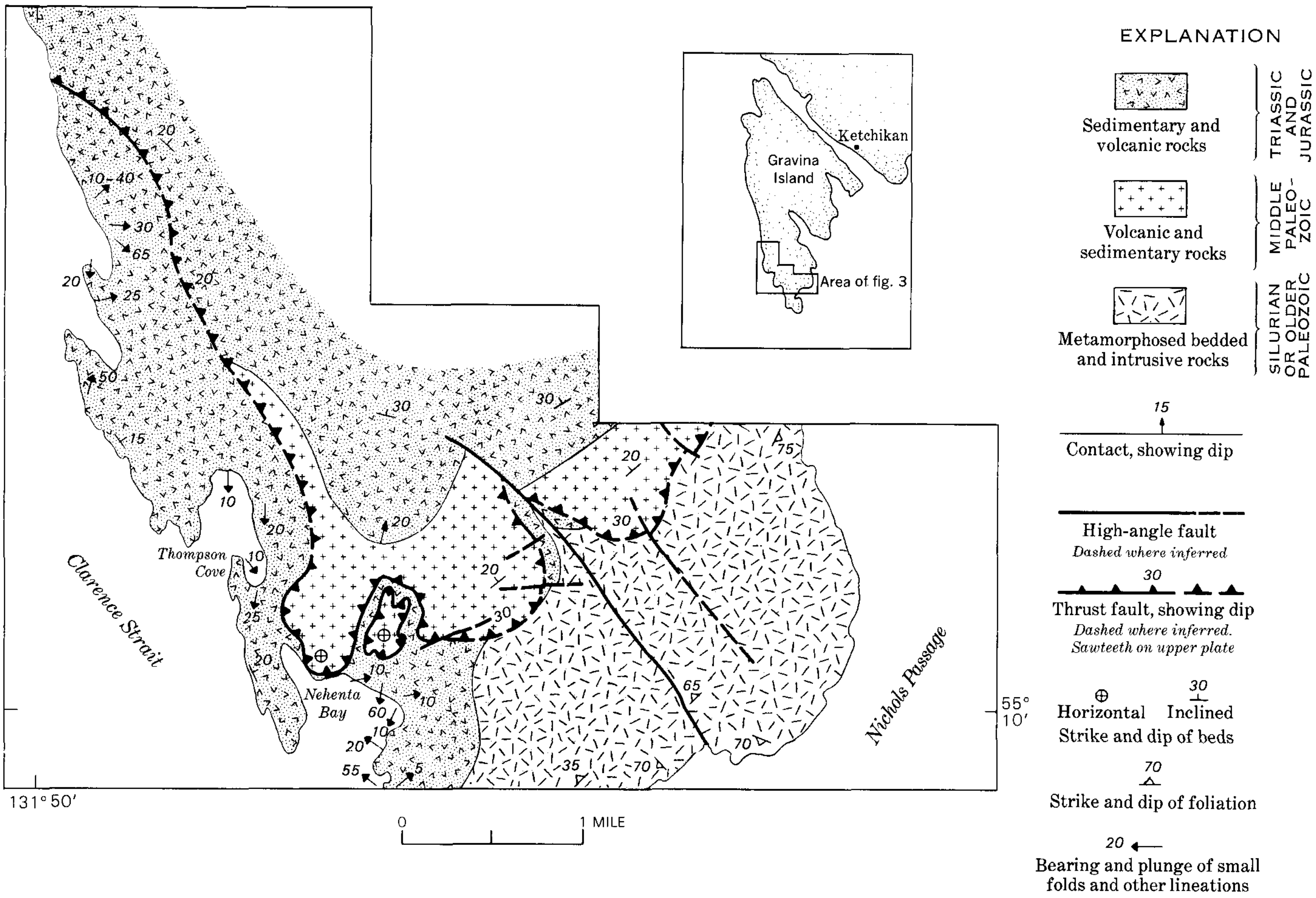

Figure 3.—Generalized geologic map of southern Gravina Island, Alaska.

hydrothermal alteration. Individual outcrops of altered fault breccia are as much as 10 feet in maximum dimension, but the thickness of the zone is unknown because exposures are poor. Areal mapping suggests that the fault thrusts Puppets metarhyolite over Silurian and older Paleozoic rocks in some places and over Upper Triassic rocks in others, but outcrops are too scattered to fully document thrusting at any single locality.

The displacement on the thrust fault on southern Gravina Island is uncertain. Its approximate stratigraphic throw, based on estimated thickness of beds faulted out by the thrust in the Nehenta Bay area, is 2,000 feet. The net slip, or total displacement, cannot be determined from the local geology, but a diagrammatic cross section of the regional geology of southwestern Gravina Island (Berg, 1973) indicates that it may be as much as a mile.

SUMMARY AND CONCLUSIONS

Late Mesozoic or Tertiary thrust faults with maximum estimated net slips of 5 miles or more—large displacements heretofore not recognized on the scattering of low-angle faults mapped elsewhere in southeastern Alaska— have been documented by detailed geologic mapping in the Annette-Gravina area near Ketchikan.

The similarity of the geology of Annette and Gravina Islands to that of many other parts of southeastern Alaska strongly suggests that thrust faults may be commonplace; but whereas reconnaissance geologic maps published to date record numerous high-angle normal, strike-slip, and reverse faults, they show only one or two low-angle faults, none with documented large-scale displacement.

Recent U.S. Geological Survey mapping in southern southeastern Alaska (A. L. Clark, A. T. Ovenshine, and H. C. Berg, unpub. data; G. D. Eberlein, and Michael Churkin, Jr., unpub. data) has revealed several major thrusts. In addition, juxtaposed dissimilar terranes and other anomalous features shown on existing geologic maps of other parts of southeastern Alaska probaly are at least partly due to major thrusting.

Recognition of this major thrusting is leading to new interpretations of southeastern Alaska's structural and tectonic history—interpretations that support such mobilistic hypotheses of large-scale tectonic dislocation and continental fragmentation as those recently proposed by Monger and Ross (1971) and Jones, Irwin, and Ovenshine (1972).

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SIGNIFICANCE OF UPPER PALEOZOIC OCEANIC CRUST IN THE UPPER CHULITNA DISTRICT, WEST-CENTRAL ALASKA RANGE

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Abstract.—An ophiolitic assemblage (ultramafic rocks, gabbro, chert, and basalt) in the Upper Chulitna district of the west-central Alaska Range is interpreted as fragmented upper Paleozoic oceanic crust incorporated into the continent. Permian through Mesozoic rocks overlying the ophiolitic assemblage record the development of an island arc followed by deposition of marine bedded rocks on continental crust. The Tertiary record indicates nonmarine deposition and intrusion of plutonic rocks. A similar history in the eastern Alaska Range shows parallel development and environmental changes.

Recent geologic investigations in the Upper Chulitna district of the west-central Alaska Range have revealed an ultramafic-mafic complex (ophiolite) that we interpret as upper Paleozoic oceanic crust. The purpose of this report is to describe this ophiolite sequence and the associated overlying strata and to speculate on their significance in the tectonic history of the Alaska Range.

The Upper Chulitna district is located on the southeast flank of the Alaska Range (fig. 1) about 130 miles north of Anchorage, Alaska, and 10 to 15 miles south of the Denali fault (figs. 1 and 2). The geology of the region has been previously studied by Capps (1919), Ross (1933), Wahrhaftig (1958), Wahrhaftig and Black (1958), Moxham, Eckhart, and Cobb (1959), Hawley and Clark (1968), Hawley and others (1969), and Hawley and Clark (1973a, b). In these earlier studies, the ultramafic-mafic rocks were interpreted as intrusive rocks of uncertain but probable Tertiary age.

The recognition of onland oceanic crust (ophiolite sequences) in many other places along the Pacific margin (Bailey and others, 1970; Richter and Jones, 1972) prompted us to reexamine the relationships in the Upper Chulitna district, where rocks of ophiolitic character were known to occur. As a result of this examination, the earlier concept of intrusive origin for the ultramafic-mafic sequence was rejected, and we now interpret these rocks as fragments of oceanic crust incorporated into the continent.

LITHOLOGIC UNITS

The rocks of the Upper Chulitna district (fig. 2) consist of an ophiolitic sequence overlain by a thick sequence of late Paleozoic to Tertiary volcaniclastic, volcanic, and sedimentary rocks of predominantly marine and subordinantly nonmarine deposition. Southeast of the ophiolitic sequence, a siliceous argillite unit of unknown age is exposed. The late Paleozoic to Tertiary bedded rocks are intruded by Tertiary(?) plutons.

Siliceous argillite

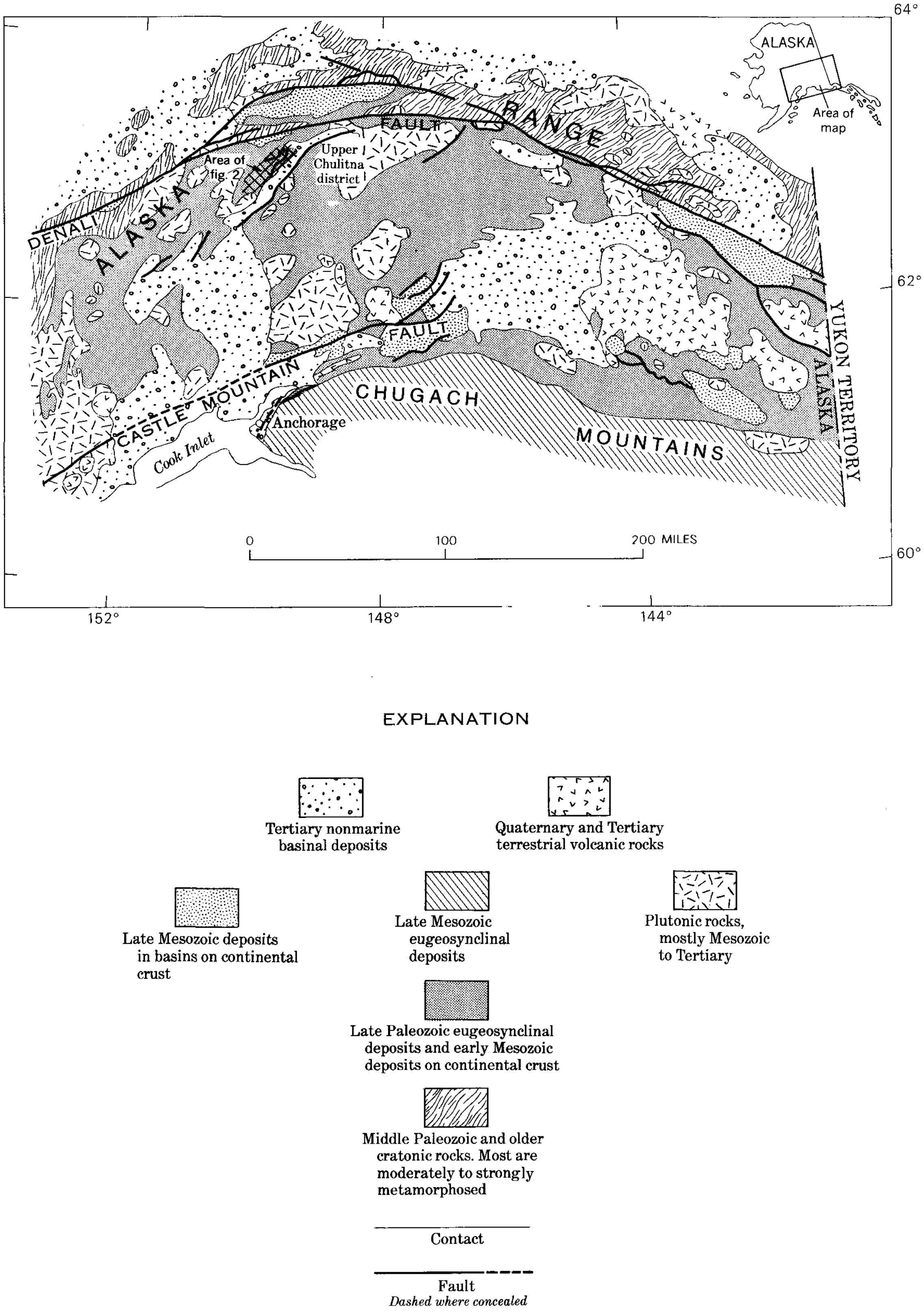
The siliceous argillite unit is composed primarily of siliceous argillite and silty argillite. Graywacke, impure quartzite, and sparse conglomerates are locally predominant.

The age of this group of rocks is unknown. Ross (1933, p. 294) correlated these rocks with rocks described by Moffit (1915, p. 24–27, 74) in the Broad Pass region that had been assigned a Devonian age by Kirk (*in* Moffit, 1915, p. 25). Because of extensive cover and large intervening distances, this correlation is highly speculative. Additional fieldwork and study will be necessary before the age of the unit is established. The contact between the siliceous argillite unit and the ophiolite sequence is interpreted as tectonic.

Ophiolitic assemblage

The ophiolitic assemblage consists of intermixed serpentinite, gabbro, basalt, and bedded chert. The serpentinite occurs as isolated bodies in a linear belt parallel to the Upper Chulitna fault zone (Hawley and Clark, 1973b) (fig. 2). The largest masses are up to 4 miles long and 100 to 5,000 feet wide; smaller masses occur locally throughout the belt. The serpentinite is black to greenish black and ranges from massive to strongly sheared. Locally, it is altered to a quartz carbonate rock. Thin-section study shows minor amounts of relict olivine and a bastite texture, suggesting that the original rock was a pyroxene-olivine ultramafic rock. The present rock is composed mainly of clinochrysotile and lizardite. Massive chromite was found in one locality.

Fine- to medium-grained basalt and gabbro form lenticular bodies intercalated with the serpentinite and also lenses and plugs on the flanks of the main belt of serpentinite. The



Fi[illegible] —Regional geologic setting of the Upper Chulitna district, Alaska. [illegible]ed from the tectonic map of North America (King, 1969).

gabbro and basalt are generally greenish black and massive. Thin-section study shows that they are composed of mainly plagioclase and pyroxene, both commonly altered, with interstitial serpentine minerals, possibly indicating the former presence of olivine. Plagioclase occurs as laths 1 to 5 mm long and 1 mm or less across. Mafic and opaque minerals fill the interstices.

The serpentinite, gabbro, and massive basalt are overlain by and locally intermixed with a sequence of approximately equal amounts of basaltic rocks, which locally show crude layering and pillow structures, and interlayered reddish-brown bedded chert and siliceous argillite. Irregular masses of red chert and carbonate are locally abundant in the basaltic layers.

The ophiolite sequence is assumed to be of Permian(?) age because it is immediately overlain by lenses of massive limestone containing Permian fossils that are described in the following section.

Volcaniclastic unit

Approximately 1,000 feet of red volcanic siltstone, sandstone, and conglomerate with interlayered limestone, tuff, sparse basalt, and, locally, quartz pebbles overlies and locally appears to grade into the ophiolitic sequence. The predominant constituents of this unit are red volcanic siltstone and conglomerate, which are interlayered on scales of a few inches to 10–20 feet. Locally, crystal tuff, massive tuff with sparse green siltstone interbeds, and volcanic conglomerate and breccia predominate. Although the conglomerate and breccia units vary widely in lithology, they are mainly volcanic pebble conglomerates with a tuffaceous matrix containing abundant crystal fragments.

Massive lenses of limestone occur near the base of the volcaniclastic sequence. These lenses contain abundant fossils, including bryzoans, crinoid columnals, pelecypods, brachiopods including *Waagenoconcha*, probably *Linoproductus*, and a large terebratuloid, *Dielasma* cf. *D. giganteum* Tschernyschew. The age of these fossils is most probably Permian, according to J. T. Dutro, Jr. (written commun., 1969).

A fossil collection from a limestone bed near the top of the volcaniclastic unit contains an abundant ammonoid fauna of Early Triassic age. The following forms were identified by N. J. Silberling (written commun., 1970):

Dieneroceras cf. *D. knechti* (Hyatt and Smith)
Euflemingites sp. indet.—immature specimen
Prosphingites cf. *P. slossi* Kummel and Steele
?*Juvenites* sp. indet.—immature specimen
Lanceolites bicarinatus Smith
Aspenites cf. *A. acutus* Hyatt and Smith
Arctoceras cf. *A. bloomstrangi* (Lindström)
Wyomingites sp. indet.

According to Silberling, this fauna is closely allied with the *Meekoceras gracilitatis* zone of the Western United States, as well as with the *Euflemingites romunderi* zone of northeastern British Columbia and arctic Canada and Alaska. Silberling and Tozer (1968) place these two zones in the lower Scythian Stage of the Early Triassic. This occurrence is the only Early Triassic fauna known from southern Alaska.

Limestone and basalt unit

The volcaniclastic unit is overlain by approximately 700 feet of calcareous siltstone, limestone, pillow basalt, and minor calcareous argillite. The lower part of this sequence is mainly fossiliferous limestone but locally contains volcaniclastic beds similar to those in the underlying unit. The middle part is mainly sandstone and siltstone, and the upper part is primarily massive limestone and pillow basalt. The limestone and pillow basalt sequence is locally at least 200 feet thick.

Fossils that are abundant in the limestone of the lower part are predominately pelecypods, gastropods, belemnites, ammonoids, and corals. R. W. Imlay (written commun., 1969) reported that the ammonite fragments are suggestive of a Triassic age. Ross (1933, p. 298–300) dated the limestones that contain corals as Early Triassic. The exact age of the limestone and pillow basalt in the upper part of the unit is unknown but is probably Late Triassic or Jurassic.

Argillite and graywacke unit

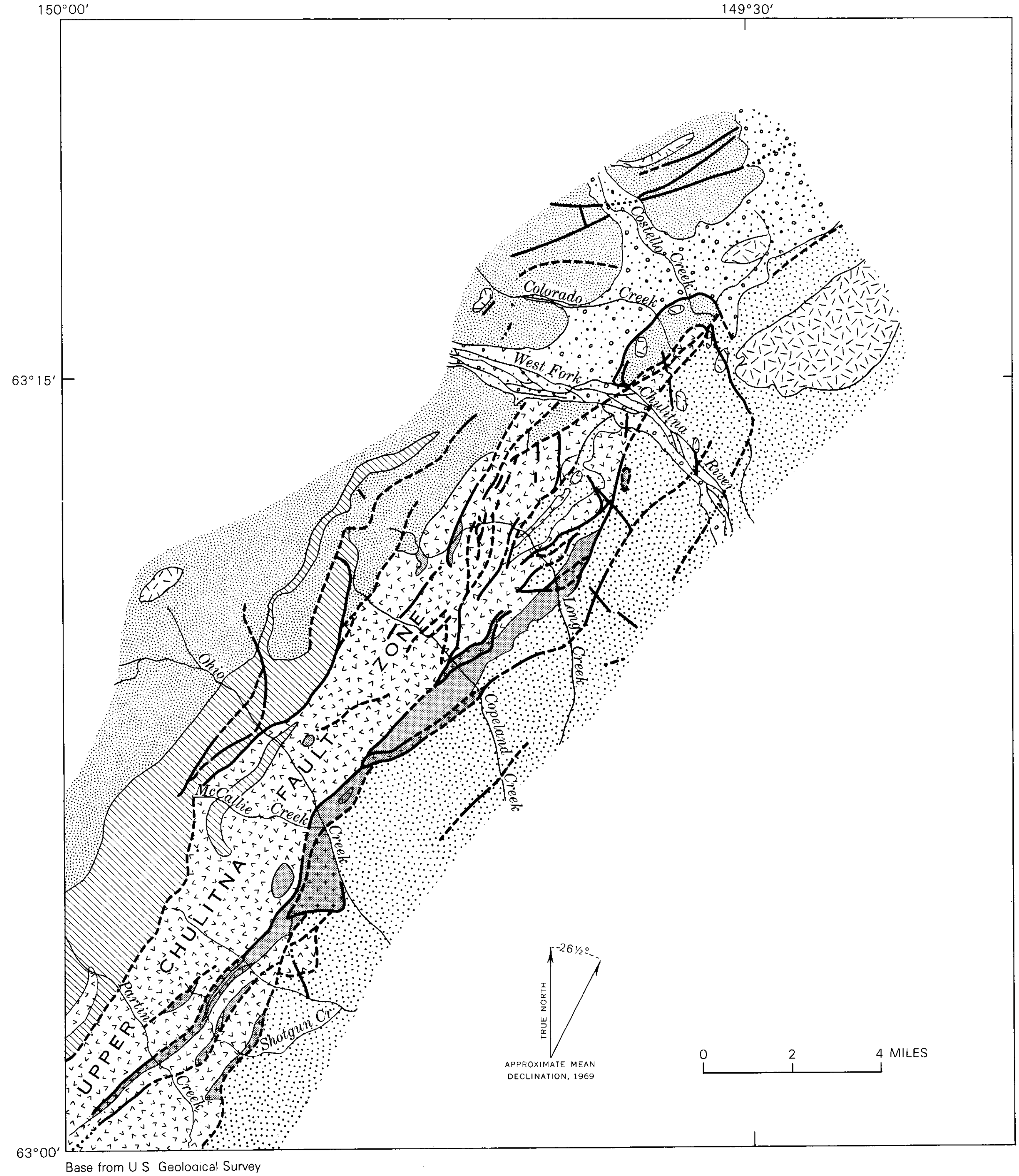
Overlying the limestone–pillow basalt unit are several thousand feet of fine- to coarse-grained detrital rocks. The unit's lowermost rocks are dark fine-grained argillites and cyclically interlayered graywacke and argillite. They are overlain by argillite, graywacke, and dark-matrix quartz argillite conglomerates that are lithologically similar to much of the lower Tertiary Cantwell Formation. Fossils collected from the lower argillite and graywacke include the pelecypod *Buchia sublaevis* (Imlay) of Early Cretaceous (Valangenian) age (D. L. Jones, written commun., 1968).

Plutonic rocks

The younger intrusive rocks are mainly diorite, quartz diorite, and granite that form small plugs and stocks without a dominant elongation direction. Geologic relations and recent potassium-argon dates obtained from a study now underway by M. A. Lanphere and B. L. Reed, U.S. Geological Survey (oral commun., 1971), indicate that the younger intrusive rocks are of early Tertiary age as proposed by Ross (1933, p. 305).

Nonmarine deposits

The youngest sedimentary rocks of the district are Oligocene (Hawley and Clark, 1973b). They are nonmarine, poorly consolidated arenaceous and carbonaceous rocks of the Costello Creek coal field. These rocks crop out in the extreme northeast part of the district and are either in unconformable



Base from U S Geological Survey
Healy quadrangle 1:250,000, 1956

Figure 2.

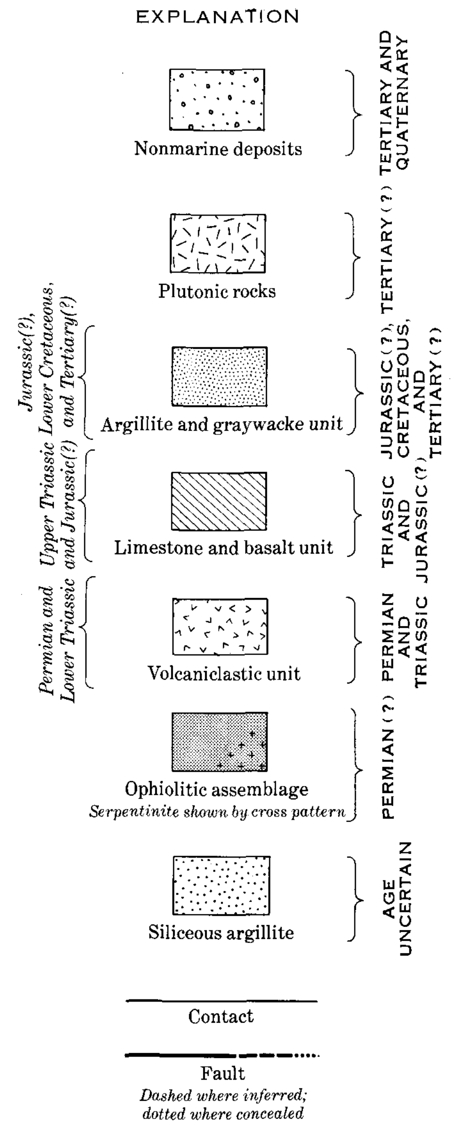


Figure 2.—Generalized geologic map of the Upper Chulitna district, Alaska. Modified from Hawley and others (1969).

or fault contact with the well-consolidated rocks of older units. The coal-bearing rocks appear to have formed in local swamps and are preserved in downwarped and downfaulted basins (Wahrhaftig, 1944).

STRUCTURE

The Upper Chulitna district is in the west-central Alaska Range south of the Denali fault, a major dextral strike-slip structure that separates the Alaska Range into two distinct geologic terranes (fig. 1). Cratonic, metamorphosed middle Paleozoic and older rocks are exposed north of the fault, whereas south of the fault the rocks are late Paleozoic and younger. The part of the Denali fault north of the Upper Chulitna district is composed of two strands, the McKinley strand on the south and the Hines Creek strand on the north. The eastern part of the Alaska Range is approximately parallel to the Denali fault (fig. 1). In the west-central Alaska Range, trends of the Denali fault and the structural trend of the Alaska Range diverge; the Alaska Range trends south-southwest toward the Alaska Peninsula, and the Denali fault trends southwest across the Kuskokwim River basin.

Rock units of the Upper Chulitna district trend approximately parallel to the trend of the Alaska Range and, although complexly folded and faulted, dip generally to the northwest, except for the southeast-dipping siliceous argillite and interlayered graywacke-argillite unit. Axial planes of asymmetric folds dip about 50° N. Major faults trend about N. 40°–50° E., approximately parallel to trends of folds and rock units and at an acute angle to the Denali fault.

INTERPRETATIONS AND COMPARISON WITH EASTERN ALASKA RANGE

The rocks of the Upper Chulitna district are interpreted in this report as recording progressive changes from oceanic crust through island-arc volcanism to a marine continental-platform environment and finally to a nonmarine basin. The record closely parallels that of the eastern Alaska Range described by Richter and Jones (1972). A summary of stratigraphy of the eastern Alaska Range, the corresponding assemblages from the Upper Chulitna district of the west-central Alaska Range, and the environments of deposition are shown in table 1.

The ophiolitic assemblage of the Upper Chulitna district is considered to be Permian(?) oceanic crust because of its resemblance to modern oceanic crust. The rocks of the overlying Permian and Triassic volcaniclastic unit indicate alternating volcanism and marine deposition. Although basalts are sparse in the unit, the clastic rock types are composed predominantly of volcanic material that imparts their characteristic red and green colors.

Because of the absence of material derived from a continental source and the proximity to the ophiolitic assemblage, the volcaniclastic rocks are thought to be derived from a volcanic island arc built directly on oceanic crust. The abundant fauna in limestones associated with the volcaniclastic rocks indicates quiet-water marine conditions at moderate to shallow depths. Recognition of the ophiolitic assemblage beneath the Permian and Triassic volcaniclastic unit in the Upper Chulitna district lends strong support to the concept of the development of a Permian island arc on oceanic crust in the eastern Alaska Range (Richter and Jones, 1972). The record of island-arc volcanism into Early Triassic time that is preserved in the west-central Alaska Range can be used to fill gaps in the record in the eastern Alaska Range.

In the Upper Triassic and Jurassic(?) limestone and basalt unit, the predominance of limestone in the lower part and absence of significant amounts of volcaniclastic rocks indicate

Table 1.—*Comparison of lithologic assemblages and depositional environments in the eastern and west-central Alaska Range*

Age	Lithologic assemblages: Upper Chulitna district of the west-central Alaska Range	Lithologic assemblages: Eastern Alaska Range (from Richter and Jones, 1972)	Depositional environment
Tertiary and Quaternary.	Arenaceous and carbonaceous sedimentary rocks, plutonic rocks.	Wrangell Lava.	Continental.
Late Cretaceous . . .	?	Nonmarine sedimentary deposits.	Continental.
Early Cretaceous . .	?	Andesitic volcanic, volcaniclastic, and minor marine sedimentary rocks.	Marine, associated volcanism in eastern Alaska Range.
Late Jurassic and Early Cretaceous.	Argillite, graywacke, and conglomerate.	Argillite and flyschlike clastic sedimentary rocks.	Marine foreland or successor basin.
Early and Middle Jurassic.	?	. . . .	
Middle and Late Triassic.	Interlayered limestone and basalt. Limestone and calcareous siltstone.	Thin limestone beds interlayered with marine shale and cherty argillite. Massive micritic limestone. Subaerial flood basalts (submarine flows in Canada). Carbonaceous shale and limestone.	Alternating marine deposition on the continental platform with subaerial volcanism in the eastern Alaska Range and submarine volcanism in the Upper Chulitna district.
Early Triassic. . . .	Volcaniclastic rocks and limestone with interlayered tuff, basalt, and locally quartz pebble conglomerate.	. . . .	
Permian		Black argillite and massive crinoidal limestone.	
		Marine volcanic and volcaniclastic rocks (may include rocks as old as Pennsylvanian).	Volcanic island arc, built directly on oceanic crust.
Late Paleozoic . . .	Ophiolitic assemblage; serpentinite, gabbro, basalt, and bedded chert.	Dunite locally; dunites and peridotites associated with pillow greenstone, and blueschists in the Kluane Range in Canada.	Oceanic crust.

a change in environment of deposition. The limestone and overlying clastic sequences are typical of marine continental-platform deposits. The sequence of pillow basalt and massive limestone in the upper part of the unit indicates periods of subaqueous volcanism alternating with carbonate accumulation. This sequence has its corollary in the eastern Alaska Range in a Triassic record of a general emergence of the continent and outpouring of a large volume of lava, followed by marine transgressions and the accumulation of limestones.

No definite record of Early or Middle Jurassic time has been identified in either the eastern or west-central Alaska Range. However, further south, this interval is recorded by Lower Jurassic volcanic and volcaniclastic rocks of the Talkeetna Formation and by Lower and Middle Jurassic marine sedimentary rocks in the southern Wrangell Mountains (MacKevett, 1969). In the central and southern Alaska Range, a major plutonic episode began in Early Jurassic time and continued for 25 million years (Reed and Lanphere, 1970).

The next record of sedimentation in both the eastern and west-central Alaska Range is the accumulation of marine graywackes, argillites, and conglomerates in Late Jurassic and Early Cretaceous time. These are foreland or successor-basin deposits on continental crust. Fossil *Buchia* are recorded in the marine sediments in both areas. Deposits equivalent to the Early and Late Cretaceous andesitic volcanic and nonmarine sedimentary rocks of the eastern Alaska Range (table 1) are not known in the Upper Chulitna district. The oldest nonmarine deposits in the district are of Tertiary age, but the sedimentary record of the Early and Late Cretaceous is absent, so that the environment during the time is not recorded.

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LISBURNE GROUP, FRANKLIN AND ROMANZOF MOUNTAINS, NORTHEASTERN ALASKA

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Abstract.—Four sections of Lisburne Group, Carboniferous (Mississippian and Pennsylvanian), were measured on autochthonous but structurally complex terrane. The section on the west end of the Sadlerochit Mountains is 1,500 feet thick and consists of Viséan (Chester) and "Namurian" (Morrow and Atoka) age carbonates. The two sections in the Franklin Mountains are in excess of 2,400 feet thick and are of Viséan (Meramec and Chester) and "Namurian" (Morrow and Atoka) age. The Romanzof Mountains section is 2,800 feet thick and of similar age. Within these sections 10 foraminiferal assemblage zones are recognized and tied to the Cordilleran and Eurasian standards. A fauna of 14 taxa of lithostrotionoid corals is present in beds of Meramec through Atoka age equivalents.

Four sections of the Lisburne Group were measured and sampled by Armstrong in 1969 and 1970 from outcrops in the Brooks Range of northeastern Alaska (fig. 1). A foraminiferal zonation for the Lisburne Group in the central and eastern Brooks Range was established by Armstrong, Mamet, and Dutro (1970) and extended by them (1971) to the Lisburne Group of the Lisburne Hills and sea cliffs of northwestern Alaska. This report is a continuation of this microfossil zonation to the Lisburne Group of the Franklin and Romanzof Mountains of northeastern Alaska. The stratigraphic section of this paper extends in an east-west direction, from the north flank to the central part of the northeastern Brooks Range (figs. 2, 3). The carbonate classification used in this report is Dunham's (1962).

A detailed historical review of stratigraphic studies of the Lisburne Group can be found in Bowsher and Dutro (1957) and Armstrong, Mamet, and Dutro (1970).

Acknowledgments.—We wish to express our appreciation to Hillard N. Reiser, the party chief during the summers of 1969 and 1970, for his generosity in supporting the stratigraphic field studies and coral collecting. We thank the Naval Arctic Research Laboratory (Barrow), Office of Naval Research, for their logistical support of fieldwork in the summers of 1969 and 1970. We are grateful to our colleagues, J. Thomas Dutro, Jr., and William J. Sando, who helped in the preparation of the manuscript and provided critical review.

STRATIGRAPHY

Endicott Group

Kekiktuk Conglomerate.—Brosgé and others (1962) named the basal sandstone beneath the Kayak(?) Shale in northeastern Alaska the Kekiktuk Conglomerate. The type section is on Whistler Creek, near the Neruokpuk Lakes (fig. 2). Brosgé and others only found indeterminate plant fragments within the formation and assigned it a Late(?) Devonian or Mississippian age, but they believed that it may represent the basal conglomerate of the overlapping Mississippian sequence. We also believe from field evidence that the Kekiktuk Conglomerate underlies the Kayak(?) Shale. The base of the Kekiktuk Conglomerate is a pebble or cobble conglomerate grading upward to coarse-grained beach or near-shore deposits that in turn commonly grade upward into finer grained paralic sediments. The contact between the Kekiktuk Conglomerate and the overlying Kayak(?) Shale is generally gradational. Possibly owing to faulting at the base, the Kekiktuk Conglomerate is absent from the bottom of section 69A-1, west end of the Sadlerochit Mountains.

The Kekiktuk Conglomerate is well exposed at the base of section 70A-4, near the Canning River. Here the Kekiktuk rests with angular unconformity on metamorphic rocks of the Neruokpuk Formation and is some 30 feet thick. It consists of basal quartz-pebble conglomerate, black carbonaceous shales, and 17 feet of strongly crossbedded light-gray quartz sandstone, and is overlain by the dark-gray Kayak(?) Shale.

The Kekiktuk Conglomerate in section 70A-2, near the junction of Marsh Fork and the Canning River, is at least 200 feet thick. It unconformably overlies the greenish-gray slates and phyllites of the Neruokpuk Formation. The lower 125 feet of the Kekiktuk Conglomerate is medium- to massive-bedded pebble conglomerates and sandstones, with quartz and hematite cement, and it has been affected by low-grade thermal metamorphism, possibly from faulting. The upper 75 feet consists of medium- to thin-bedded quartz sandstone, dark-gray siltstones, dark-gray shales, thin (1 in. or less) coal

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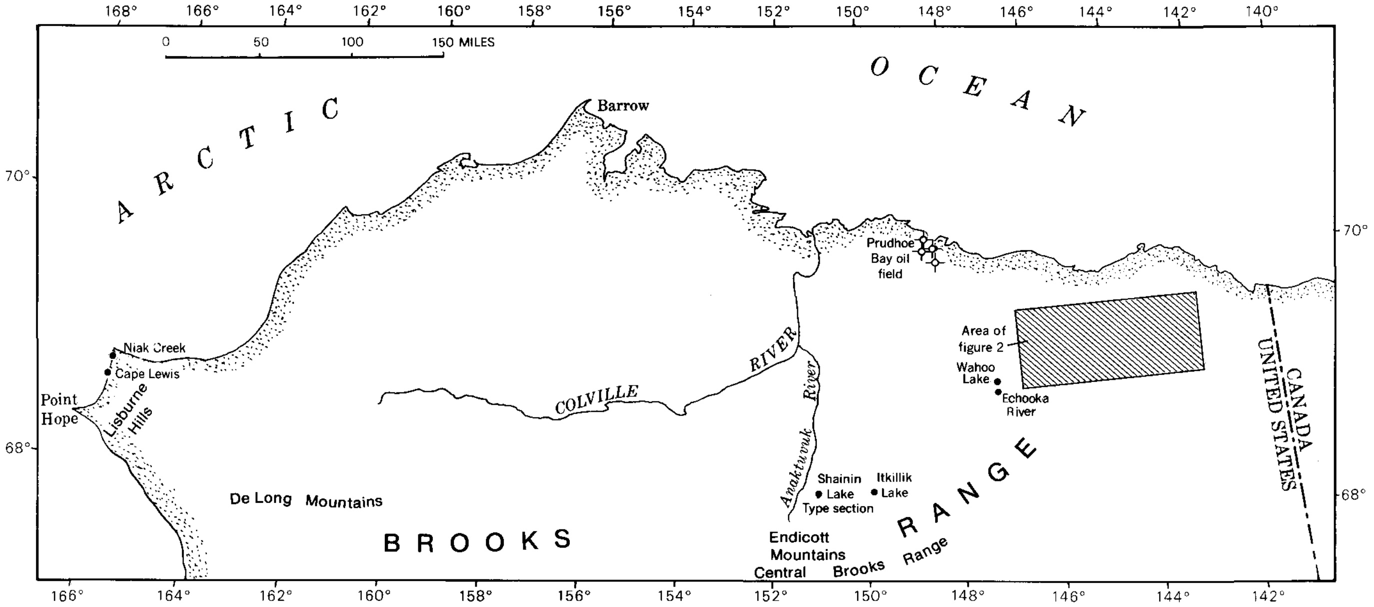

Figure 1.—Index map of arctic Alaska, showing location of the study area (fig. 2) containing the stratigraphic sections shown on figure 3.

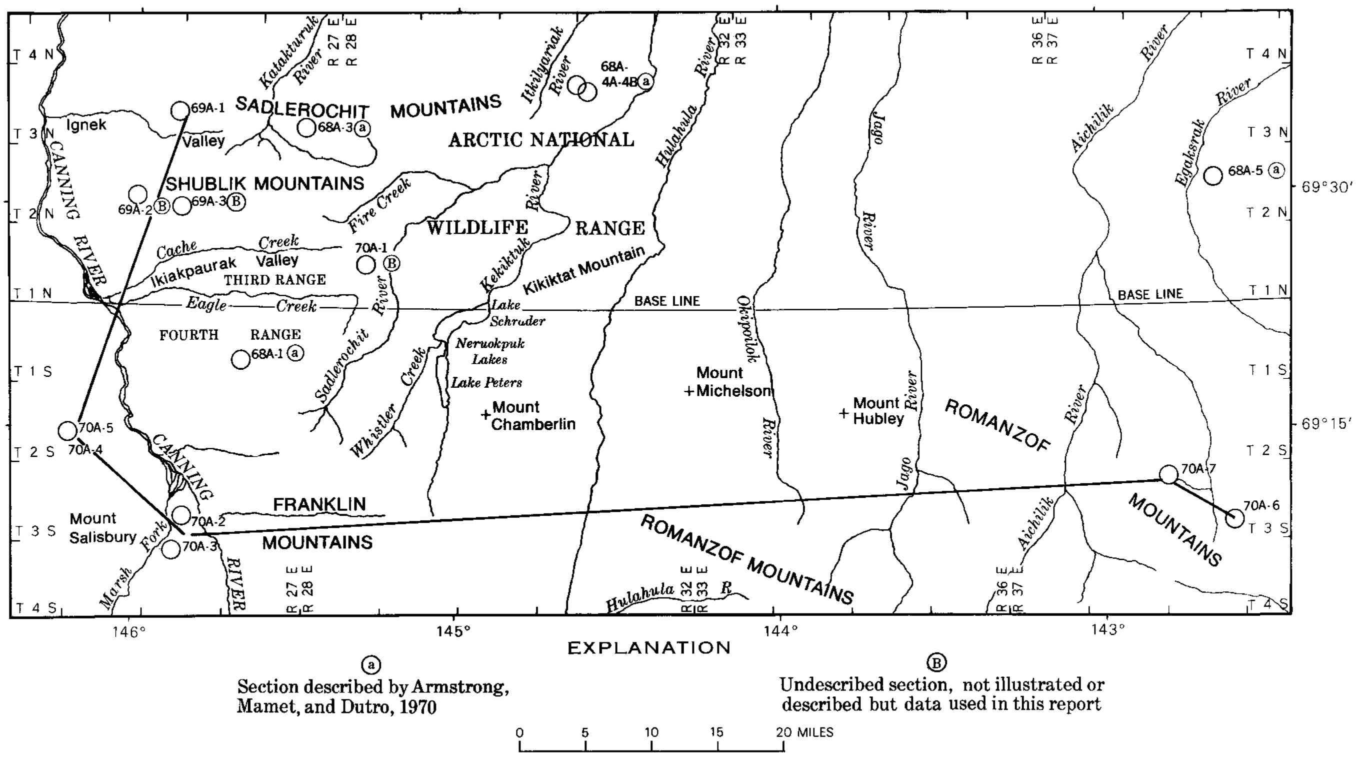

Figure 2.—Index map showing location of measured sections.

beds and abundant plant remains. The contact with the overlying Kayak(?) Shale is transitional, and the boundary between the two formations was arbitrarily picked.

The section 70A-7 on the north flank of the large synclinorium east of the Aichilik River contains about 100 feet of quartzite conglomerates, sandstones, and shales. The contact between the upper sandstones of the Kekiktuk Conglomerate and the Kayak(?) Shale is poorly exposed, but it appears to be a gradational zone about 50 feet thick.

Kayak(?) Shale.—Mississippian dark-gray to black shales lie beneath carbonate rocks of the Lisburne Group throughout the eastern and central Brooks Range. Bowsher and Dutro

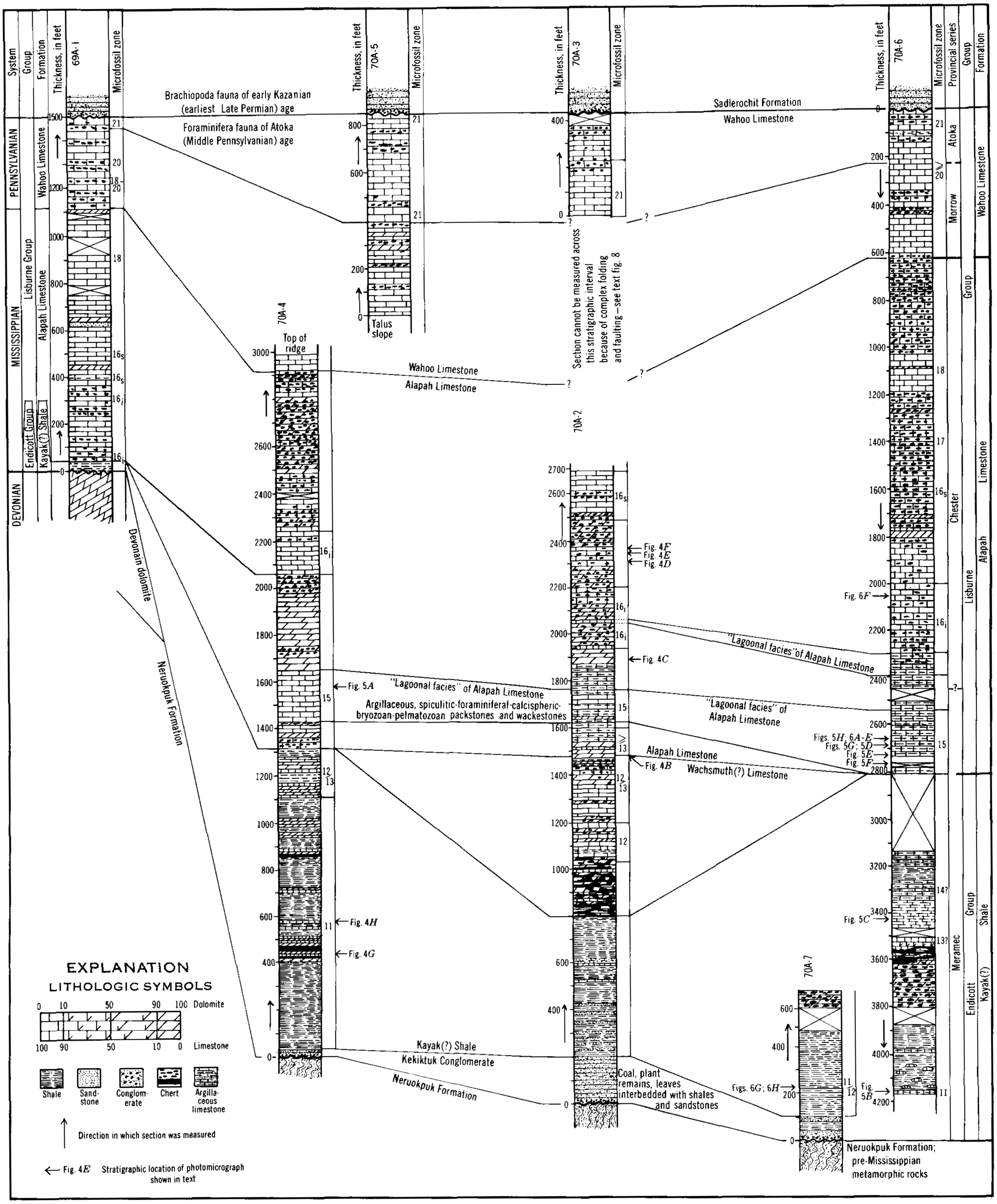

Figure 3.—Biostratigraphic correlation diagram of the Lisburne Group, northeastern, Alaska.

(1957, p. 6) in the Endicott Mountains named these the Kayak Shale, from the type section on the south side of Mount Wachsmuth, east of Shainin Lake. The Kayak Shale at its type locality and in the Endicott Mountains is Early Mississippian in age. Adjacent to and east of the Canning River, in the Arctic National Wildlife Range, a similar black shale occurs between the Kekiktuk Conglomerate and the Lisburne Group. Brosgé and others (1962) believed "this shale is at least in part of Late Mississippian age." They further stated, "Because of geologic structure, this shale can not be mapped continuously into the type Kayak. It might therefore be a discrete unit entirely younger than the Kayak and separated from the Kayak by a disconformity within the Mississippian rocks." Following Brosgé and others (1962), the shales in the area of this report are called Kayak(?) Shale.

The Kayak(?) Shale is thin, only about 50 feet thick in the western Sadlerochit Mountains. In section 69A-1 this brownish-gray calcareous unit rests unconformably on dolomites of Devonian age. The overlying basal beds of the Alapah Limestone are lower Chester in age, and probably the thin Kayak(?) Shale is of similar age. In section 70A-4, about 27 miles to the south (fig. 3), the unit thickens markedly and is older; it contains microfossils of Meramec, zone 11, age (fig. 3). Approximately 1,220 feet thick, it is a sequence of dark-gray shales, thin-bedded argillaceous lime mudstones, dolomites, and thin-bedded dark-gray to black cherts. The upper 100 to 200 feet of the unit becomes progressively more calcareous upward, and the contact with the Alapah Limestone is gradational.

The Kayak(?) Shale, 11 miles to the southeast in section 70A-2, is only about 600 feet thick (fig. 3). The predominant rock type is dark-gray shale, with only minor amounts of thin-bedded sandstones, siltstones, and yellow-weathering thin-bedded limestone (figs. 4*G*, 4*H*). The base of the unit is gradational with the Kekiktuk Conglomerate, which contains abundant plant remains. At the top of the Kayak(?) Shale there is an abrupt change from dark-gray shales to dark-gray bedded spiculitic cherts and dolomites.

The composite section 70A-6 and 70A-7 of the Kayak(?) Shale about 84 miles east of section 70A-2 is about 1,450 feet thick; the lower 450 feet is dark-gray shale with a few thin lime mudstone beds and nodules (fig. 5*B*, 5*C*). Above this segment is 300 feet of highly siliceous, argillaceous, cherty, gray and dark-gray dolomites and limestones. The upper 700 feet of the unit is calcareous dark-gray shale and thin-bedded argillaceous dark-gray coralliferous limestones. The contact with the basal Alapah Limestone is gradational.

Lisburne Group

In the Shainin Lake area, Endicott Mountains, Bowsher and Dutro (1957, p. 3, 4, 6) recognized two new formations within the Lisburne which they raised to group rank. The lower formation is the Wachsmuth Limestone, and the overlying one is the Alapah Limestone. Armstrong, Mamet, and Dutro's (1970, figs. 3, 4) study indicates that the age of the Wachsmuth based on microfossils is late Osage zone 8 through zone 12 and Meramec.

They found that the Alapah Limestone contains microfaunas of Meramec (transition of zones 12 and 13) through Chester (zone 19) ages.

Because the vast majority of the carbonate rocks of this study are younger than zone 12, the Wachsmuth carbonate facies is evidently very poorly represented. The interval 800 to 1,475 feet of section 70A-2 is considered to be a possible Wachsmuth equivalent.

Brosgé and others (1962, p. 2191–2192) described the type section of the Wahoo Limestone near Wahoo Lake as containing carbonates of both Pennsylvanian(?) and Permian age. In the area of this report, the Wahoo Limestone as mapped by Reiser and others (1970) may contain carbonates of Late Mississippian (very latest Chester) and Early and Middle Pennsylvanian age (Morrow and Atoka). The Pennsylvanian limestones overlie Mississippian carbonates without a recognizable hiatus. The boundary between the two systems and the zones within them are based on microfaunal assemblages. The beds of Atoka age are unconformably overlain by Late Permian arenaceous limestones, sandstones, and conglomerates in the lowest part of the Sadlerochit Formation.

Alapah Limestone.—As illustrated in figure 3, the base of the Lisburne Group is diachronous. The contact with the Kayak(?) Shale in section 70A-2 at the Junction of Marsh Fork and Canning River is Meramec, zone 12 in age, whereas 31 miles to the north the oldest beds of the Alapah Limestone are lower Chester, zone 16. The basal 100 feet of the Alapah Limestone at section 70A-2 is formed of black nodular and bedded chert and argillaceous dark-gray spiculite-lime mudstone. Bedded cherts are common at the base of many Lisburne exposures in the Franklin and Romanzof Mountains. Above the cherts are about 300 feet of bryozoan-pelmatozoan wackestones, and packstone and dolomite (fig. 4*B*), followed by a characteristic marker zone approximately 200 to 350 feet thick, the so-called "lagoonal facies" of the Alapah Limestone. In outcrop, these are gray medium-bedded argillaceous limestones, with little or no chert. The rock is typically argillaceous, may have birdseye structure, and is made up of spiculitic-foraminiferal-calcispheric-bryozoan-pelmatozoan-pelletoid packstones and wackestones. In sections 70A-4 and 70A-2 of the Franklin Mountains and section 70A-6 of Romanzof Mountains, the Chester-age beds of the Alapah Limestone are typically shallow-water lime mudstones and bryozoan-pelmatozoan-pelletoid wackestones and packstones (figs. 4*C*–4*F*; 5*A*, 5*D*–5*H*; 6*A*–6*G*). Dolomite is common and occurs in the limestones as scattered rhombs; it also forms thick units of bedded fine- to medium-grained dolomite rock. The Alapah Limestone in section 69A-1, on the west end of the Sadlerochit Mountains, is only 1,100 feet thick. The lower part of the section is pelmatozoan-bryozoan-ooid packstones and grainstones that grade upwards into wackestones and pelletoid mudstones with a few beds of fine-grained dolomite.

The Alapah Limestone in the Franklin and Romanzof Mountains in outcrop shows little variation in lithology and bedding (figs. 7 and 8); it is typically medium to dark gray, has medium bedding, and shows few sedimentary structures. The upper third to half of the unit in sections 70A-4, 70A-2, and in particular 70A-6, contains abundant nodular, dark-gray to gray chert. (fig. 7).

Wahoo Limestone.—The Wahoo Limestone on the west end of the Sadlerochit Mountains is about 400 feet thick and consists primarily of pelmatozoan-bryozoan wackestone, packstones, and grainstones, and beds of ooid packstones and grainstones. The ooid facies of the units is generally absent in the sections studied in the Franklin and Romanzof Mountains. Here the unit is from 600 to 900 feet thick and consists of medium- to massive-bedded, gray to light-gray, slightly cross-bedded pelmatozoan-bryozoan wackestone and packstones, and minor amounts of grainstone. Occasional beds of thin dolomite and superficial ooid packstones may be present. Chert is typically nodular, light gray to brown and generally occurs in the lime-mud-rich beds. The contact (fig. 7) between the Wahoo and Alapah Limestones is generally sharp, marked by the darker gray, thinner bedded lime mudstones and wackestones of the Alapah Limestone overlain by the thicker bedded, lighter gray pelmatozoan wackestones and packstones of the Wahoo Limestone.

In the area of this study the Permian and Triassic Sadlerochit Formation unconformably overlies limestones of Atoka age. Detterman (1970) reports that the basal Echooka Member of the Sadlerochit Formation contains a brachiopod fauna of early Kazanian, earliest Late Permian age. The unconformity between the Wahoo Limestone and Sadlerochit Formation represents a hiatus of Des Moines through Leonard and, possibly, lower Guadalupe time.

Armstrong, Mamet, and Dutro (1970) have illustrated the westward thinning of the Atoka age carbonates in the Sadlerochit Mountains. This thinning and the northward thinning shown in figure 3 suggest uneven erosion, probably from differential uplift before deposition of the Sadlerochit Formation. At many localities the highest few feet of Atoka age carbonates beneath the Sadlerochit Formation shows evidence of vadose weathering in the form of enlarged vertical joints and vugs filled with a clay similar to terra rossa. The basal beds of the Echooka Member of the Sadlerochit Formation are conglomerates or conglomeratic sandstone formed partly of rounded chert and limestone pebbles and cobbles derived from the underlying Wahoo Limestone.

BIOSTRATIGRAPHY

Microfaunal assemblage zones

The microfaunal assemblage zones used in this study have been used by Mamet and Gabrielse (1969), Mamet and Mason (1968), and Mamet (1968) to correlate the Carboniferous of western Canada with the Carboniferous of the northern Cordillera of the United States (Sando and others, 1969). Armstrong, Mamet, and Dutro (1970, 1971) also used these zones to correlate the Lisburne Group of the eastern and central Brooks Range and the Lisburne Hills region of northwestern Alaska (fig. 9).

The microfacies of Alaska, as in most of the Taimyr-Alaska foraminiferal realm (Mamet, 1962; Mamet and Belford, 1968; Mamet and Skipp, 1970), are generally poor in foraminifers and algae. Within the sections of the Lisburne Group studied in this report of northeastern Alaska, 10 foraminiferal assemblages can be recognized and correlated with the Cordilleran and Eurasiatic Carboniferous zonations (Sando and others, 1969).

Late Tournaisian (middle and late Osage).—Microfaunas of this age or older have not been found in the stratigraphic sections of this report, but they were reported by Armstrong, Mamet, and Dutro (1970) from outcrops of the Lisburne Group in the Endicott Mountains, to the west. There the late Tournaisian Zones 8(?) and 9 have been found only in the basal part of the Shainin Lake and Itkillik Lake sections. These sections are characterized by the acme of the Tournayellidae, represented by *Glomospiranella, Septabrunsiina, Septatournayella,* and *Tournayella discoidae.* The spinose endothyrida, *Tuberendothyra* and *Spinoendothyra,* generally abundant at that level in the northern Cordillera of the United States and adjacent Canada are very scarce.

In the American cordillera, similar zones are known in the Shunda Formation of the Fort St. John region in southern Alberta. They also are observed in the Livingstone Formation of southwestern Alberta, in the lower part of the Mission Canyon Limestone of Montana and western Wyoming, and in the upper part of the Madison Limestone of central Wyoming (Sando and others, 1969). These zones are present in the Keokuk Limestone of the American midcontinent, in particular in its type section.

Early and early middle Viséan.—Armstrong, Mamet, and Dutro (1970) report that in the central Brooks Range (Endicott Mountains) no characteristic microfauna of the earliest Viséan zone 10 is known; the passage between the Tournaisian-Viséan is either barren or in a nondiagnostic *Earlandia* facies. In the sections described in this report, no microfossils of zone 10 are known, and strata that could be an equivalent stratigraphic level to zone 10 are black shales of the Kayak(?) Shale or are sandstone and siltstone. The late early Viséan zone 11 and early middle Viséan zone 12 are characterized by *Globoendothyra baileyi,* numerous species of *Stacheia-Stacheoides* and *Eoendothyranopsis,* and, in zone 12, *Koninckopora.* Similar faunas are known in the middle part of the Prophet Formation and in the lower part of the Debolt Formation in the Fort St. John region, in the middle part of the Flett Formation of the Northwest Territories, in the lower part of the Mount Head Formation in southwestern Alberta

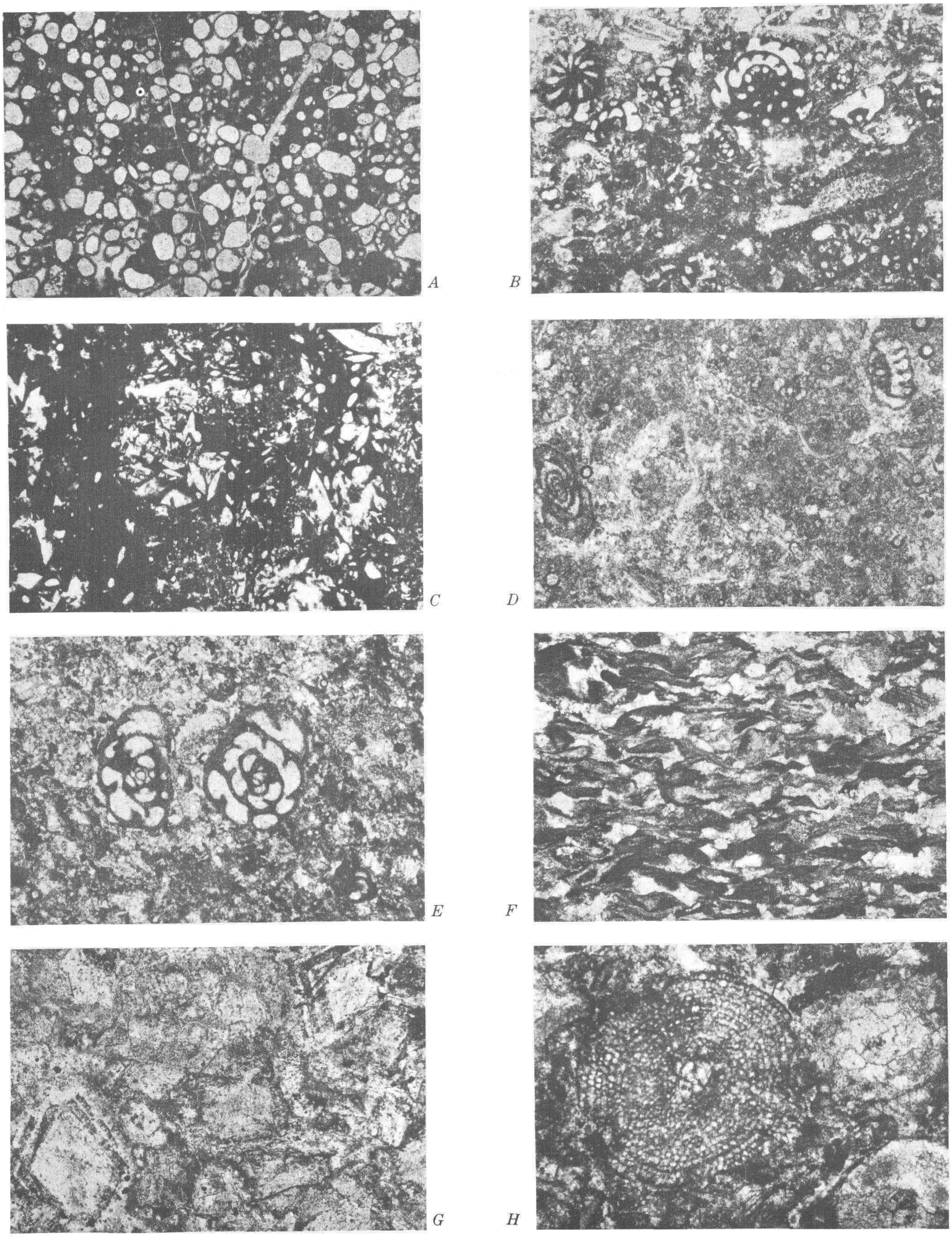

Figure 4.

Figure 4.—Photomicrographs of microfacies and microfossils of sections 70A-1, 70A-2, and 70A-4 of the Alapah Limestone and Kayak(?) Shale, northeastern Alaska.

A. Section 70A-1, 40 ft above base, × 25, Alapah Limestone, zone 13, late middle Viséan, St. Louis equivalent. Well sorted, rolled pelmatozoans and lumps of grainstone. Crinoids are usually resistant to abrasion; this is an unusual example of worn, reworked ossicles. Base of Alapah Limestone, east end of Third Range.

B. Section 70A-2, 1,475 ft above base, × 25, Alapah Limestone?, transition of zones 12 and 13, middle Viséan, Salem-St. Louis transition. Poorly sorted foraminiferal-algal packstone. *Eoendothyranopsis* of the group *E. spiroides* (Zeller), *Eoendothyranopsis hinduensis* (Skipp), *Eoendothyranopsis* sp., *Endothyra* sp., and *"Issinella"* sp. are conspicuous.

C. Section 70A-2, 1,890 ft above base, × 25, Alapah Limestone, undetermined zone 15 or 16_i?, late Viséan, uppermost Meramec or lowermost Chester equivalent. Calcite pseudomorphs after gypsum.

D. Section 70A-2, 2,310 ft above base, × 25, Alapah Limestone, undetermined zone 16_i or 16_s?, late Viséan, lower Chester equivalent. *Eostaffella* sp. and *Calcisphaera* sp. in a slightly recrystallized wackestone.

E. Section 70A-2, 2,340 ft above base, × 25, Alapah Limestone, undetermined zone 16_i or 16_s?, late Viséan, lower Chester equivalent. *Globoendothyra* sp. and *Globoendothyra paula* (Vissarionova) in a recrystallized, poorly sorted wackestone. Minute calcispheres and rare pellets are present.

F. Section 70A-2, 2,360 ft above base, × 25, Alapah Limestone, undetermined zone 16_i or 16_s?, late Viséan, lower Chester equivalent. Tectonically stressed limestone, deformed bryozoan fronds and brachiopod shells give a fluid appearance to the rock.

G. Section 70A-4, 435 ft above base, × 63, Kayak(?) Shale, zone 11, early Viséan, Salem equivalent. Dolomitized pelmatozoan-bryozoan packstone(?). Succession of calcite/dolomite carbonate generations is emphasized by silver nitrate staining.

H. Section 70A-4, 570 ft above base, × 30, Kayak(?) Shale, zone 11, early Viséan, Salem equivalent. Although recrystallization is fairly advanced, the wall structure of the red algae (*Stacheia* sp.) is still recognizable, and the regular subquadratic morphology of the cells is well displayed.

(Petryk and others, 1970), in the upper part of the Mission Canyon Limestone of Montana and western Wyoming, and in the uppermost part of the Madison Limestone of central Wyoming (Sando and others, 1969, zones 10 and 11 only). *Globoendothyra baileyi* and *Eoendothyranopsis spiroides* are common in the middle part of the Salem Limestone in its type region, and *Globoendothyra baileyi-Eoendothyranopsis spiroides* and *Koninckopora* are known in the upper part of the Salem Limestone.

Late middle and early late Viséan.—In Alaska, zone 13 is usually found in facies favorable to calcareous foraminifers (Armstrong, Mamet, and Dutro, 1970), such as pseudo-oolitic packstone, grainstone, or algal wackestone and packstone; hence, the assemblages of *Globoendothyra-Eoendothyranopsis, Endothyranopsis*, and *Archaediscus* of the group *A. krestovnikovi* are usually rich and diversified. *Eoendothyranopsis* of the group *E. pressa* (*E. scitula* Toomey) is present.

In contrast, zones 14 and 15 (St. Louis and Ste. Genevieve Limestones) are difficult to identify because the "*Brunsia* facies," which indicates abnormal salinity, eliminates most of the characteristic normal marine representatives of *Eoendothyranopsis* and *Endothyranopsis.* The "*Brunsia* facies" is found as far south as northeastern British Columbia and southeastern Yukon Territory.

The *Eoendothyranopsis pressa* fauna (zones 13–15) is known in the upper part of the Debolt Formation (Macauley, 1958, p. 298) of Fort St. John, in the upper part of the Mount Head Formation of southwestern Alberta (Lummus, Marston, Carnarvon, and Opal Members; Petryk and others, 1970), in the Middle Canyon Formation and in the basal part of the Scott Peak Formation of Huh (1967) in southwestern Idaho, and in the Little Flat Formation and lower part of the Monroe Canyon Limestone in the Idaho depositional province (Sando and others, 1969). This fauna is also a major one in the St. Louis and Ste. Genevieve Limestones of Missouri.

Late Viséan (early Chester).—Zones 16_i and 16_s are recognizable mainly from the presence of Archaediscidae and Endothyridae; Meramec fauna, such as *Eoendothyranopsis* or *Eoforschia*, are absent, and the *Neoarchaediscus-"Eostaffella" discoidea* fauna progressively becomes a major feature; the base of zone 16_s is drawn where *Neoarchaediscus incertus* and *Planospirodiscus* occur abundantly.

Both zones are known in the basal part of the Nizi Formation of British Columbia (Mamet and Gabrielse, 1969), in the lower Etherington Formation of southwestern Alberta (Mamet, 1968), in the upper part of the Scott Peak Formation and in the South Creek Formation in the Lost River Range, Idaho (Huh, 1967), and in the middle part of the Monroe Canyon Limestone in the Idaho depositional province (Sando and others, 1969). The zones are also present from the Aux Vases Sandstone to the Golconda Formation of the Chester type region.

Namurian (middle to upper Chester and Morrow).—The *Eumorphoceras* foraminiferal equivalents (zones 17 and 18) are recognized in the successive bursts of growth of *Asteroarchaediscus baschkiricus* and *Globivalvulina*(?) *parva.* These assemblages are known in an unnamed recessive interval succession of northern Yukon; in the Calico Bluff Formation, Yukon River, east-central Alaska; in the middle and upper part of the Nizi Formation in northern British Columbia; in Mississippian rocks on the Prince of Wales Island, southeastern Alaska; in the middle and upper parts of the Etherington Formation of southeastern British Columbia (Mamet, 1968); in the Surrett Canyon Formation of Huh (1967) in the Lost River Range, Idaho; in the upper part of the Monroe Canyon Limestone of the Idaho depositional province (Sando and others, 1969); and in the middle part of the Amsden Formation in Wyoming. In the midcontinent region, these zones are observed from the Glen Dean Limestone to the Kinkaid Limestone.

The microfauna of zone 19 was not found within the

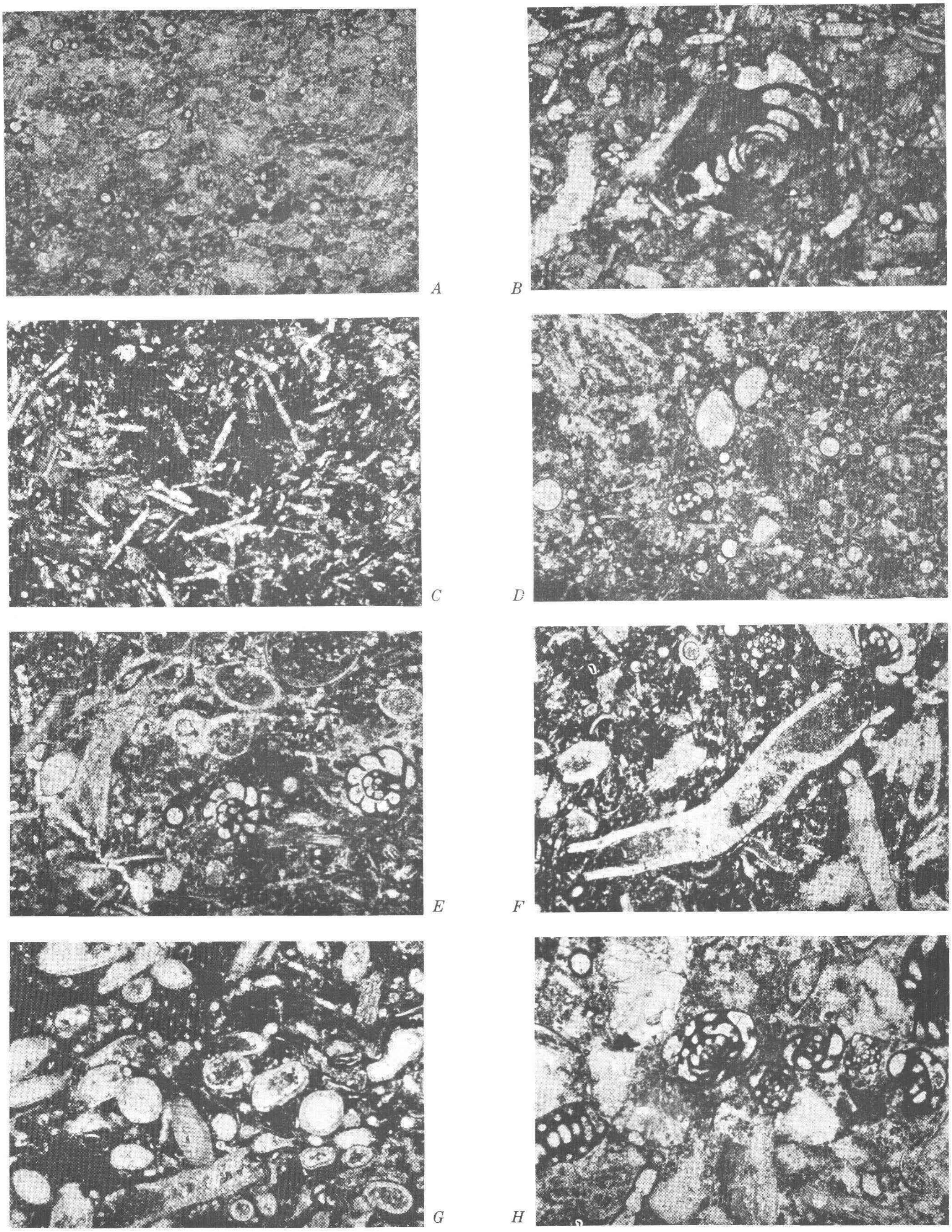

Figure 5.

Figure 5.—Photomicrographs of microfacies and microfossils of sections 70A-4 and 70A-6 of the Alapah Limestone and Kayak(?) Shale, northeastern Alaska.

A. Section 70A-4, 1,570 ft above base, × 25, Alapah Limestone, zone 15, late Viséan, Ste. Genevieve equivalent. Lagoonal, recrystallized grainstone and packstone. Abundant calcispheres (*Calcisphaera* sp.), *Parathurammina* sp., *Vicinesphaera* sp., and *Girvanella* sp. are conspicuous.

B. Section 70A-6, 4,165 ft from the top, × 25, Kayak(?) Shale, zone 11, early Viséan, Salem equivalent. Equatorial section of "*Septatournayella*" *henbesti* Skipp, Holcomb, and Gutschick in a dark, poorly sorted packstone.

C. Section 70A-6, 3,425 ft from the top, × 25, Kayak(?) Shale, zone 14? late Viséan, St. Louis equivalent? Sponge spiculite.

D. Section 70A-6, 2,690 ft from the top, × 25, Alapah Limestone, zone 15, late Viséan, Ste. Genevieve equivalent. Lagoonal, calcisphere-rich wackestone (*Calcisphaera laevis* Williamson, "*Radiosphaera*"). Ostracodes, and *Parathurammina* sp. and *Endothyra* sp. are also present.

E. Section 70A-6, 2,730 ft from the top, × 25, Alapah Limestone, zone 15, late Viséan, Ste. Genevieve equivalent. Poorly sorted packstone. *Endothyranopsis compressa* (Rauzer-Chernoussova and Reitlinger), *Calcisphaera pachysphaerica* (Pronina), *Earlandia* sp., *Kamaena* sp., and "*Issinella*" sp. are conspicuous.

F. Section 70A-6, 2,775 ft from the top, × 25, Alapah Limestone, zone 15, late Viséan, Ste. Genevieve equivalent. "*Issinella*" packstone. *Endothyranopsis* sp., *Calcisphaera* sp., and *Endothyra* sp. are also present.

G. Section 70A-6, 2,690 ft from the top, × 25, Alapah Limestone, zone 15, late Viséan, Ste. Genevieve equivalent. "*Issinella*" packstone.

H. Section 70A-6, 2,660 ft from the top, × 25, Alapah Limestone, zone 15, late Viséan, Ste. Genevieve equivalent. Foraminiferal-pelmatozoan packstone. *Eoendothyranopsis* of the group *E. pressa-E. rara* (*Eoendothyranopsis scitula* Toomey), *Eoendothyranopsis robusta* (McKay and Green), *Endothyra* sp., *Earlandia* sp., *Calcisphaera* sp., and *Earlandinella* sp. are conspicuous.

sections of this report. Zone 19, the *Homoceras* foraminiferal partial equivalent (*Eosigmoilina*?), is known in some of the Sadlerochit Mountains sections (Armstrong, Mamet, and Dutro, 1970) and is the probable equivalent of the basal Baschkirian of the Russian platform. *Homoceras* equivalents appear to be scarce in North America, although the *Eosigmoilina*? fauna has been identified in the upper part of the Surrett Canyon Formation of Huh (1967) in Idaho, in the upper part of the Indian Springs Formation of Rich (1963) in Nevada, and in scattered localities in the Great Basin. The zone is absent by hiatus in the American midcontinent.

Zone 20, characterized by the appearance of the *Lipinella-Millerella* sensu stricto assemblage, could be equivalent to part of the late Baschkirian of the Russian platform. If so, the zone would straddle the Namurian-Westphalian boundary (Gordon, 1964). However, the upper part of the late Baschkirian contains *Profusulinella*, whereas, in zone 22, this fusulinid is known only in the American cordillera. The zone-20 assemblage is known in the basal part of the Pennsylvanian System of Idaho and in the upper part of the Amsden Formation in central and western Wyoming. Zone 20 corresponds to the Morrow Series in the midcontinent.

Undetermined late Carboniferous.—The highest Carboniferous zone identified in this report is zone 21, recognized by the outburst of *Eoschubertella-Pseudostaffella*, associated with *Globivalvulina* sensu stricto. The zone is known in the basal part of the lower limestone unit in Yukon and in the upper part of the Amsden Formation of the Wyoming depositional province. It is present in the basal Atoka Series (Middle Pennsylvanian) of the midcontinent.

No post-Atoka microfaunas are reported here from the Wahoo Limestone.

Microfossils found in the Lisburne Group in the report area are given in the following tabulation:

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska

[Stratigraphic locations are shown on figure 3]

Section 70A-2
  Interval: 1,090–1,195 feet
    Calcisphaera laevis Williamson
    Calcisphaera pachysphaerica (Pronina)
    Dainella sp.
    Earlandia of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
    Earlandinita sp.
    "*Endothyra*" of the group *E.*? *prisca* Rauzer-Chernoussova and Reitlinger
    Eoendothyranopsis sp.
    Eoendothyranopsis hinduensis (Skipp)
    Eoendothyranopsis of the group *E. spiroides* (Zeller)
    "*Eoendothyranopsis*" *redwallensis* (Skipp)
    Globoendothyra sp.
    Globoendothyra of the group *G. baileyi* (Hall)
    Globoendothyra of the group *G. tomiliensis* (Grozdilova)
    Parathurammina sp.
    Stacheia sp.
    Stacheoides sp.
  Age: zone 12

  Interval: 1,390–1,475 feet
    Calcisphaera sp.
    Earlandia sp.
    Endothyra sp.
    Eoendothyranopsis sp.
    Eoendothyranopsis hinduensis (Skipp)
    Eoendothyranopsis of the group *E. pressa–E. rara* (Grozdilova in Lebedeva)
    Eoendothyranopsis scitula (Toomey)
    Eoendothyranopsis of the group *E. spiroides* (Zeller)
    "*Issinella*" sp.
    Globoendothyra sp.
    Kamaena sp.
    Tetrataxis sp.
  Age: transition of zones 12 and 13

  Interval: 1,495–1,600 feet
    Archaediscus sp.
    Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
    Brunsia sp.
    Calcisphaera sp.

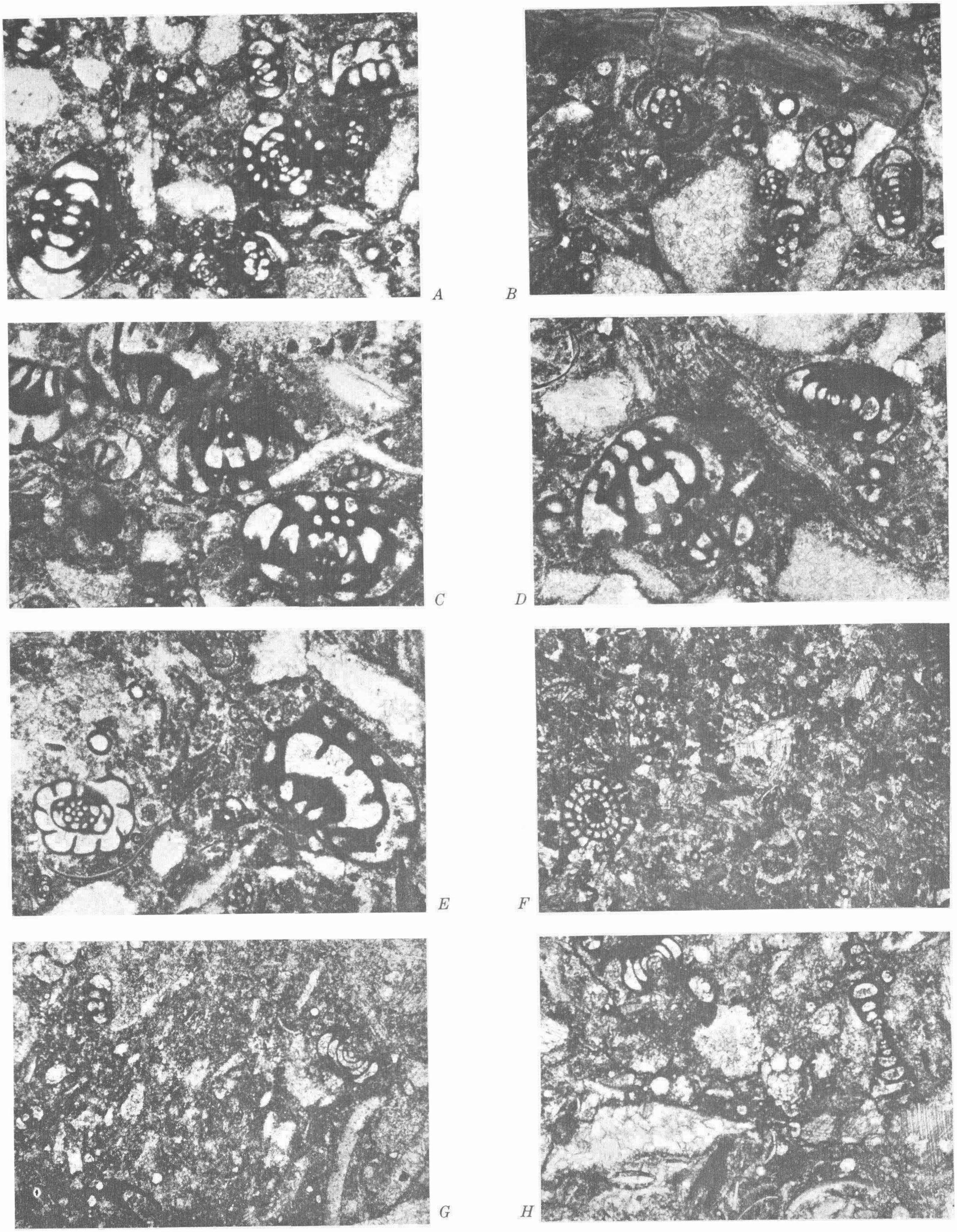

Figure 6.

Figure 6.—Photomicrographs of microfacies and microfossils of sections 70A-6 and 70A-7 of the Alapah Limestone and Kayak(?) Shale, northeastern Alaska.

A–E. Section 70A-6, 2,660 ft from the top, × 25, Alapah Limestone, zone 15, middle late Viséan, Ste. Genevieve equivalent. An exceptionally rich foraminiferal-pelmatozoan-brachiopodal wackestone. Foraminifers are abundant and represented mostly by Endothyranopsidae; *Eoendothyranopsis* of the group *E. ermakiensis* (Grozdilova *in* Lebedeva), *Eoendothyranopsis robusta* (McKay and Green), and *Endothyranopsis compressa* (Rauzer-Chernoussova and Reitlinger). *Calcisphaera pachysphaerica* (Pronina), *Calcisphaera* sp., *Globoendothyra* sp., and *Endothyra* sp. are also noticeable.

F. Section 70A-6, 2,055 ft from the top, × 25, Alapah Limestone, zone 16_i or 16_s undetermined, late Viséan, lower Chester equivalent. Equatorial section of *Eostaffella* sp. and scattered calcispheres in a recrystallized wackestone. Some cement present.

G and *H*. Section 70A-7, 230 feet from the base, × 25, Alapah Limestone, zone 11, early Viséan, Salem equivalent. Slightly recrystallized wackestone and packstone. *Earlandia* of the group *E. clavatula* (Howchin), *Earlandia* of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger), *Parathurammina* sp., *Eoforschia* sp., and *"Septatournayella"* are present.

Figure 7.—Photograph of the contact between the Alapah and Wahoo Limestones in section 70A-6. Note the relatively uniform bedding within the Alapah Limestone.

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-2—Continued
Interval: 1,495–1,600 feet—Continued
"Cornuspira" sp.
Dainella sp.
Earlandia sp.
Endothyra sp.
Endothyranopsis sp.
Eoendothyranopsis of the group *E. ermakiensis* (Grozdilova in Lebedeva)

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-2—Continued
Interval: 1,495–1,600 feet—Continued
Eoendothyranopsis of the group *E. pressa–E. rara* (Grozdilova in Lebedeva)
"Eoendothyranopsis" redwallensis (Skipp)
Eoendothyranopsis scitula (Toomey)
Globoendothyra sp.
Kamaena sp.
Koninckopora inflata (de Koninck)
Parathurammina sp.
Planoarchaediscus? sp.
Stacheia sp.
Stacheoides sp.
Tetrataxis sp.
Age: zone 13

Interval: 1,650 feet
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
Brunsia sp.
Calcisphaera laevis Williamson
Calcisphaera pachysphaerica (Pronina)
"Cornuspira" sp.
Earlandia of the group *E. clavatula* (Howchin)
Earlandia of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
Earlandinella sp.
Endothyra sp.
"Endothyra" of the group *E.*? *prisca* Rauzer-Chernoussova and Reitlinger
Endothyranopsis compressa (Rauzer-Chernoussova and Reitlinger)
Endothyranopsis crassa (Brady)
Eoendothyranopsis of the group *E. ermakiensis* (Grozdilova in Lebedeva)
Eoendothyranopsis of the group *E. pressa–E. rara* (Grozdilova in Lebedeva)
Eoendothyranopsis robusta (McKay and Green)
Globoendothyra of the group *G. tomiliensis* (Grozdilova)
Globoendothyra of the group *G. globulus* (d'Eichwald)
Globoendothyra paula (Vissarionova)
"Issinella" sp.
Kamaena sp.
Koninckopora inflata (de Koninck)
Parathurammina sp.
Stacheia sp.
Stacheoides sp.
Yukonella sp.
Age: zone 15

Interval: 1,960–2,186 feet
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
Calcisphaera sp.
"Cornuspira" sp.
Endothyra of the group *E. bowmani* Phillips in Brown emend Brady
Epistacheoides sp.
Globoendothyra of the group *G. globulus* (d'Eichwald)
Kamaena sp.
Parathurammina sp.
Pseudoglomospira sp.
Stacheia sp.
Stacheoides sp.
Zellerina sp.
Age: zone 16_i

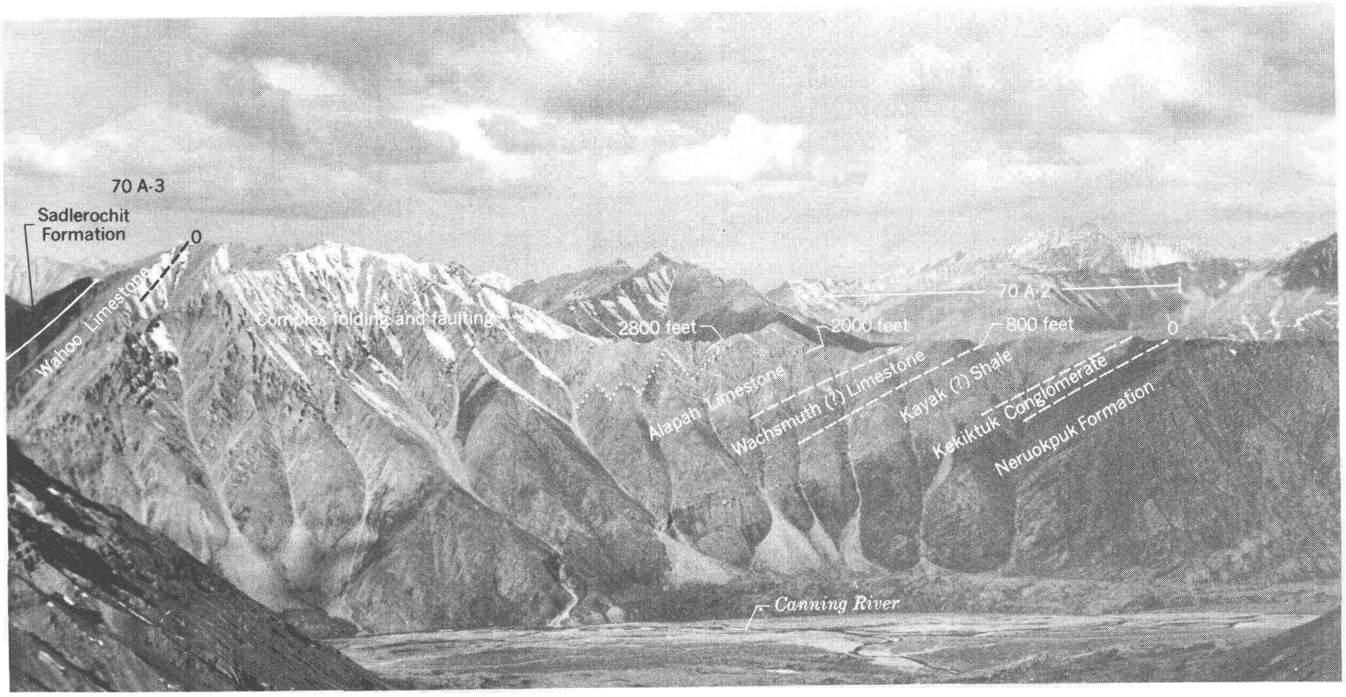

Figure 8.—Photograph of sections 70A-2 and 70A-3 viewed to the west. The contact (dashed line) of the Neruokpuk Formation with the Kekiktuk Conglomerate is well exposed on the outcrop. The interval between sections 70A-2 and 70A-3 is marked by complex folding and faulting. The contact between the Wahoo Formation and the Sadlerochit Formation is indicated by solid line on the left side of the photograph.

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-2—Continued
  Interval: 2,490—2,696 feet
    Archaediscus sp.
    Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
    Calcisphaera sp.
    "*Cornuspira*" sp.
    Endothyra sp.
    Neoarchaediscus sp.
    Neoarchaediscus of the group *N. incertus* (Grozdilova and Lebedeva)
    Pseudoglomospira sp.
  Age: zone 16_s

Section 70A-3
  Interval: 0—240 feet
    Archaediscus sp.
    Asphaltina sp.
    Asteroarchaediscus sp.
    Asteroarchaediscus baschkiricus (Krestovnikov and Teodorovitch)
    Biseriella sp.
    Climacammina sp.
    Endothyra sp.
    Eoschubertella sp.
    Eostaffella sp.
    Globivalvulina of the group *G. bulloides* Brady
    Globoendothyra sp.
    Globoendothyra of the group *G. globulus* (d'Eichwald)
    Lipinella sp.
    Millerella sp.
    Neoarchaediscus sp.

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-3—Continued
  Interval: 0—240 feet—Continued
    Neoarchaediscus of the group *N. incertus* (Grozdilova and Lebedeva)
    Orthovertella sp.
    Planoendothyra sp.
    Planospirodiscus sp.
    Pseudoendothyra britishensis Ross
    Pseudostaffella sp.
    Tetrataxis sp.
    Zellerina sp.
  Age: zone 21

Section 70A-4
  Interval: 435—690 feet
    Calcisphaera sp.
    Earlandia sp.
    Endothyra sp.
    Eoendothyranopsis sp.
    Globoendothyra of the group *G. baileyi* (Hall)
    Parathurammina sp.
    Stacheia sp.
    Stacheoides sp.
    Tetrataxis sp.
  Age: zone 11

  Interval: 1, 160—1,210 feet
    Calcisphaera sp.
    Earlandia sp.
    Endothyra sp.

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-4—Continued
- Interval: 1,160–1,210 feet—Continued
  - "*Endothyra*" of the group *E.*? *prisca* Rauzer-Chernoussova and Reitlinger
  - *Eoendothyranopsis* of the group *E. pressa*–*E. rara* (Grozdilova in Lebedeva)
  - *Eoendothyranopsis* of the group *E. spiroides* (Zeller)
  - *Eoendothyranopsis scitula* (Toomey)
  - *Globoendothyra paula* (Vissarionova)
  - *Stacheia* sp.
- Age: transition of zones 12 and 13

- Interval: 1,310 feet
  - *Archaediscus* sp.
  - *Calcisphaera* sp.
  - *Earlandia* sp.
  - *Endothyra* sp.
  - *Eoendothyranopsis* of the group *E. pressa*–*E. rara* (Grozdilova in Lebedeva)
  - *Eoendothyranopsis scitula* (Toomey)
  - *Stacheia* sp.
- Age: zone 13

- Interval: 1,410–1,650 feet
  - *Archaediscus* of the group *A. krestovnikovi* Rauzer-Chernoussova
  - *Brunsia* sp.
  - *Calcisphaera laevis* Williamson
  - *Calcisphaera pachysphaerica* (Pronina)
  - *Earlandia* of the group *E. clavatula* (Howchin)
  - *Earlandia* of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
  - *Endothyra* of the group *E. bowmani* Phillips in Brown emend Brady
  - "*Endothyra*" of the group *E.*? *prisca* Rauzer-Chernoussova and Reitlinger
  - *Endothyranopsis compressa* (Rauzer-Chernoussova and Reitlinger)
  - *Endothyranopsis crassa* (Brady)
  - *Eoendothyranopsis* of the group *E. ermakiensis* (Grozdilova in Lebedeva)
  - *Eoendothyranopsis robusta* (McKay and Green).
  - *Girvanella* sp.
  - *Globoendothyra* of the group *G. globulus* (d'Eichwald)
  - *Globoendothyra paula* (Vissarionova)
  - "*Issinella*" sp.
  - *Kamaena* sp.
  - *Parathurammina* sp.
  - *Planoarchaediscus*? sp.
  - *Stacheia* sp.
  - *Stacheoides* sp.
  - *Vicinesphaera* sp.
  - *Yukonella* sp.
- Age: zone 15

- Interval: 2,050–2,235 feet
  - *Aoujgalia* sp.
  - *Archaediscus* sp.
  - *Archaediscus* of the group *A. krestovnikovi* Rauzer-Chernoussova
  - *Earlandia* sp.
  - *Endothyra* sp.
  - "*Endothyra*" of the group *E.*? *prisca* Rauzer-Chernoussova and Reitlinger

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-4—Continued
- Interval: 2,050–2,235 feet—Continued
  - *Eostaffella* sp.
  - *Globoendothyra* sp.
  - *Parathurammina* sp.
  - *Stacheia* sp.
  - *Stacheoides* sp.
  - *Zellerina* sp.
- Age: zone 16_i

Section 70A-5
- Interval: 380–840 feet
  - *Aoujgalia*? sp.
  - Apterrinellids
  - *Archaediscus* sp.
  - *Asphaltina* sp.
  - *Asteroarchaediscus* sp.
  - *Asteroarchaediscus baschkiricus* (Krestovnikov and Teodorovitch)
  - *Biseriella* sp.
  - *Climacammina* sp.
  - *Endothyra* sp.
  - *Eoschubertella* sp.
  - *Globivalvulina* sp.
  - *Globivalvulina* of the group *G. bulloides* Brady
  - *Globoendothyra* sp.
  - "*Issinella*" sp.
  - *Komia* sp.
  - *Neoarchaediscus* sp.
  - *Neoarchaediscus parvus* (Rauzer-Chernoussova)
  - *Palaeotextularia* sp.
  - *Planoendothyra* sp.
  - *Planospirodiscus* sp.
  - *Pseudoendothyra* sp.
  - *Pseudoendothyra britishensis* Ross
  - *Pseudoglomospira* sp.
  - *Pseudostaffella* sp.
  - Stacheiinae
  - *Tetrataxis* sp.
  - *Zellerina* sp.
- Age: zone 21

Section 70A-6
- Interval: 4,150–4,165 feet
  - *Calcisphaera laevis* Williamson
  - *Calcisphaera pachysphaerica* (Pronina)
  - *Earlandia* of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
  - *Endothyra* sp.
  - *Eoforschia* sp.
  - *Globoendothyra* of the group *G. baileyi* (Hall)
  - *Latiendothyra* sp.
  - *Parathurammina* sp.
  - "*Septatournayella*" *henbesti* Skipp, Holcomb, and Gutschick
  - *Stacheia* sp.
  - *Stacheoides* sp.
- Age: zone 11

- Interval. 3,510–3,515
  - *Archaediscus krestovnikovi* Rauzer-Chernoussova
  - *Calcisphaera* sp.

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-6—Continued
Interval: 3,510–3,515—Continued
Earlandia sp.
Endothyra sp.
Eoendothyranopsis of the group *E. pressa–E. rara* (Grozdilova in Lebedeva)
Eoforschia sp.
Globoendothyra of the group *G. tomiliensis* (Grozdilova)
Stacheia sp.
Stacheoides sp.
Age: zone 13 or younger

Interval: 3,290–3,315 feet
Brunsia sp.
Brunsia lenensis Bogush and Yuferev
Brunsia irregularis (von Möller)
Earlandia sp.
Globoendothyra sp.
Age: probably zone 14?

Interval: 2,570–2,795 feet
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
Calcisphaera sp.
Calcisphaera laevis Williamson
Calcisphaera pachysphaerica (Pronina)
Earlandia of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
Earlandinella sp.
Endothyra sp.
Endothyranopsis sp.
Endothyranopsis compressa (Rauzer-Chernoussova and Reitlinger)
Eoendothyranopsis sp.
Eoendothyranopsis of the group *E. ermakiensis* (Grozdilova in Lebedeva)
Eoendothyranopsis of the group *E. pressa–E. rara* (Grozdilova in Lebedeva)
Eoendothyranopsis scitula (Toomey)
Eoendothyranopsis robusta (McKay and Green)
Girvanella sp.
Globoendothyra sp.
Globoendothyra of the group *G. globulus* (d'Eichwald)
Globoendothyra paula (Vissarionova)
"*Issinella*" sp.
Kamaena sp.
Parathurammina sp.
"*Radiosphaera*" sp.
Stacheia sp.
Stacheoides sp.
Vicinesphaera sp.
Age: zone 15

Interval: 1,970–2,360 feet
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
Calcisphaera laevis Williamson
Calcisphaera pachysphaerica (Pronina)
"*Cornuspira*" sp.
Earlandia sp.
Earlandia of the group *E. clavatula* (Howchin)

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-6—Continued
Interval: 1,970–2,360 feet—Continued
Earlandia of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
Endothyra sp.
"*Endothyra*" of the group *E.? prisca* Rauzer-Chernoussova and Reitlinger
Eostaffella sp.
Globoendothyra sp.
Parathurammina sp.
Pseudoendothyra sp.
Pseudoglomospira sp.
cf. *Planoendothyra* sp.
Zellerina sp.
Age: zone 16_i

Interval: 1,600–1,630 feet
Archaediscus sp.
Archaediscus of the group *A. krestovnikovi* Rauzer-Chernoussova
Endothyra sp.
Eostaffella sp.
Globoendothyra sp.
Neoarchaediscus sp.
Planospirodiscus sp.
Pseudoendothyra sp.
Pseudoglomospira sp.
Tetrataxis sp.
"*Tetrataxis*" of the group *T.? eominima* Rauzer-Chernoussova
Age: zone 16_s

Interval: 1,420–1,400 feet
Archaediscus sp.
Asteroarchaediscus sp.
Asteroarchaediscus baschkiricus (Krestovnikov and Teodorovitch)
Endothyra sp.
Neoarchaediscus sp.
Planospirodiscus sp.
Age: zone 17

Interval: 1,160–1,180 feet
Archaediscus sp.
Asteroarchaediscus sp.
Biseriella parva (Chernysheva)
"*Cornuspira*" sp.
Endothyra sp.
Neoarchaediscus sp.
Age: zone 18

Interval: 310–380 feet
Asphaltina sp.
Biseriella sp.
Endothyra sp.
Globivalvulina sp.
Age: zone 20 or younger

Interval: 0–115 feet
Archaediscus sp.
Asphaltina sp.
Asteroarchaediscus sp.

Microfossils of the Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska—Continued

[Stratigraphic locations are shown on figure 3]

Section 70A-6—Continued
  Interval: 0–115 feet—Continued
    Asteroarchaediscus baschkiricus (Krestovnikov and Teodorovitch)
    Biseriella sp.
    Endothyra sp.
    Eoschubertella sp.
    Eostaffella sp.
    Globivalvulina sp.
    Globivalvulina bulloides Brady
    Globoendothyra sp.
    Lipinella sp.
    Neoarchaediscus sp.
    Orthovertella sp.
    Planoendothyra sp.
    Planospirodiscus sp.
    Pseudoendothyra sp.
    Pseudostaffella sp.
    Tetrataxis sp.
    Trepeilopsis sp.
    Zellerina sp.
  Age: zone 21

Section 70A-7
  Interval: 230–250 feet
    Calcisphaera sp.
    Calcisphaera laevis Williamson
    Earlandia sp.
    Earlandia of the group *E. clavatula* (Howchin)
    Earlandia of the group *E. vulgaris* (Rauzer-Chernoussova and Reitlinger)
    Eotuberitina sp.
    Endothyra sp.
    Earlandinella? sp.
    Eoforschia sp.
    Globoendothyra of the group *G. baileyi* (Hall)
    cf. *Latiendothyra* sp.
    "*Septatournayella*" *henbesti* Skipp, Holcomb, and Gutschick
    Stacheia sp.
    Stacheoides sp.
  Age: transition of zones 11 and 12

Lithostrotionoid coral zones

Lithostrotionoid corals are abundant in the Meramec-age parts of the Alapah Limestone and common in the Atoka-age beds of the Wahoo Limestone. They are rare in Chester-age beds (fig. 10).

The lithostrotionoid corals collected from northeastern Alaska belong to the same taxa that are prolific in the shallow-water shelf carbonates of the Lisburne Group in the central and western Brooks Range (Armstrong and Mamet, 1970; Armstrong, Mamet and Dutro, 1971; Armstrong, 1970, 1972a, 1972b).

Large stratigraphic coral collections were made from section 70A-2, from 855 to 2,200 feet above the base. The Wahoo Limestone from 15 to 100 feet above the base of section 70A-3 yielded several colonies of *Corwenia* sp. (figs, 3, 8). Smaller collections of Mississippian corals were made in the Alapah Limestone of section 70A-4. The Wahoo Limestone about 590 feet above the base of section 70A-5 has numerous tabulate corals belonging to the genus *Michelinia* sp. The Romanzof Mountains section 70A-6 contains a sparse coral fauna, relative to that in section 70A-2. No colonial corals were found in the Kayak(?) Shale in stratigraphic levels 3,200 feet below the top of the section. These beds are argillaceous limestone of zones 13? and 14? that was probably unfavorable for coral growth. Within all these sections corals are generally abundant in the cleaner, less argillaceous limestones of zones 12 through 15. In zones 16_s and 16_i above, *Lithostrotionella* aff. *L. mclareni* (Sutherland) is generally the only coral. The Alapah Limestone in the west Sadlerochit Mountains section, 69A-1, which is Chester in age and occurs 1,120 feet above the base, contains *Lithostrotion (Siphonodendron)* sp. in zone 18. The Wahoo Limestone at this section contains, in zone 21, numerous *Lithostrotionella* of Atoka age (Pennsylvanian).

The known stratigraphic distribution of lithostrotionoid corals in the Lisburne Group (Mississippian and Pennsylvanian) of northeastern Alaska is shown in figure 10. This figure, when compared with a similar illustration by Armstrong, Mamet, and Dutro (1970, fig. 9) for the lithostrotionoid corals of northwestern Alaska, reveals certain differences. In the Lisburne Hills sea cliffs and the De Long Mountains, the large and diversified Meramec coral fauna persists into the lower part of zone 16_i (lowest Chester), whereas, in the northeastern Brooks Range, stratigraphic evidence suggests that this coral fauna disappears at the end of zone 15. This late Meramec extinction conforms with Macqueen and Bamber's (1968) evidence from the Mount Head Formation of southwestern Alberta that shows the extinction of the *L. (S.) warreni* Nelson, *Thysanophyllum astraeiforme* (Warren), and *Lithostrotionella mclareni* (Sutherland) fauna at the end of Meramec (zone 15) time. Significant changes in the stratigraphic range of certain coral species are documented by the large coral collections from limestones in the Romanzof and Franklin Mountains. The stratigraphic range in the Lisburne Group of *Lithostrotion (Siphonodendron) sinuosum* (Kelly); *L. (S.) warreni* Nelson; *Sciophyllum alaskaensis* Armstrong; and *Thysanophyllum astraeiforme* (Warren) is extended into zone 12.

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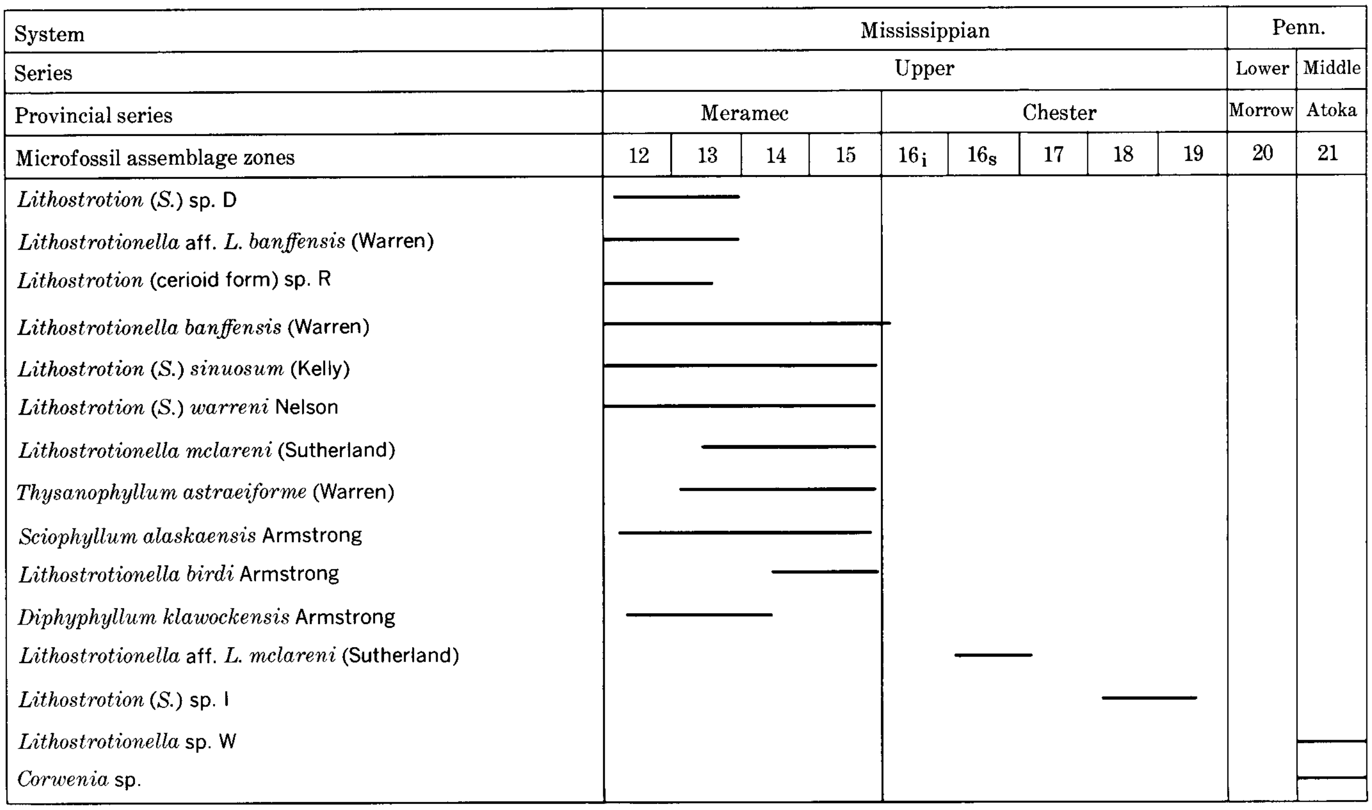

Figure 10.—Stratigraphic range chart of the lithostrotionoid corals in the Lisburne Group of northeastern Alaska.

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GEOCHEMISTRY AND DISTRIBUTION OF PLATINUM-GROUP METALS IN MAFIC TO ULTRAMAFIC COMPLEXES OF SOUTHERN AND SOUTHEASTERN ALASKA

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Abstract.—Rock types and platinum-group metal concentrations were studied in seven mafic to ultramafic complexes in southern and southeastern Alaska. Anomalous concentrations of platinum-group metals correlate with rock types, oxide and sulfide phases, and major and trace elements. The correlations are consistent within an individual complex but differ for each complex. The occurrence of anomalous concentrations of platinum-group metals within the zoned ultramafic complexes shows that these bodies (particularly the complex at Union Bay) and the platiniferous zoned ultramafic bodies of the Ural Mountains, U.S.S.R., are even more similar than previously recognized.

Over 50 mafic to ultramafic complexes are known in southern and southeastern Alaska. The southeastern belt of zoned complexes (fig. 1) has been described by Taylor (1967, p. 99) as being almost identical with the platiniferous ultramafic complexes of the Ural Mountains, U.S.S.R. However, of all the mafic to ultramafic complexes in southern and southeastern Alaska, only the complex at Salt Chuck on Prince of Wales Island has produced appreciable amounts of platinum and palladium (Mertie, 1920), mainly as a byproduct of copper mining operations. To date, six complexes—at Union Bay, Duke Island, Blashke Islands, Eklutna, Salt Chuck, and Klukwan—have been studied by the authors. (See Clark and Greenwood, 1972, p. C21–C27, this chapter.) Data presented in this report on the complex at Mount Fairweather are from a report by Plafker and MacKevett (1970).

This paper presents preliminary data on the concentration of platinum-group metals in the mafic to ultramafic complexes studied and defines the elements and rock types most commonly associated with anomalous platinum metal concentrations in each.

Acknowledgments.—The five assay-spectrographic determinations of platinum-group metals were made by J. C. Negri, R. R. Carlson, and E. F. Cooley, and their services are gratefully acknowledged.

SETTING AND GENERAL GEOLOGY

The mafic to ultramafic complexes described in this report, with the exception of the complex at Mount Fairweather, occur within two distinct belts in southern and southeastern Alaska (fig. 1). The southeastern belt, described by Taylor and Noble (1960), is approximately 30 miles wide and 350 miles long. The southern Alaska belt, which includes the Eklutna ultramafic body, is less well known but probably extends from Kodiak Island on the southwest to beyond the Canadian border on the east. The complex at Mount Fairweather occurs approximately midway between the two belts.

The general characteristics of the ultramafic complexes in the southeastern Alaska belt have been discussed by Taylor and Noble (1960) and Taylor (1967). Reconnaissance and detailed geologic and petrographic studies have been made on all of the mafic to ultramafic complexes studied in this report (Mertie, 1920; Walton, 1951; H. P. Taylor, Jr., and R. H. Stebbins, unpub. data; Ruckmick and Noble, 1959; Irvine, 1963; Rose, 1966; and Plafker and MacKevett, 1970).

All the complexes studied are grossly similar in several aspects:

1. Olivine-bearing rocks occur near the center of the concentrically zoned complexes of the southeastern Alaska belt and near the base of the complexes in the southern Alaska belt (Sandra H. B. Clark, oral commun., 1970), indicating that both belts contain differentiated bodies.
2. Clinopyroxene, primarily diopsidic hedenbergite, occurs in all but the complex at Mount Fairweather, in which Plafker and McKevett (1970, p. B24) have reported both clinopyroxenes and orthopyroxenes in pyroxene gabbro samples.
3. Magnetite is commonly present and locally constitutes 15 to 20 percent of pyroxenite and hornblendite bodies. Ilmenite occurs as a major accessory mineral in all rock types and is normally associated with magnetite.
4. Chromite is commonly present, locally constituting up to 5 to 10 percent of dunite bodies. Chromite normally occurs as disseminations, isolated pods, and stringers and rarely (Eklutna) as discontinuous layers.

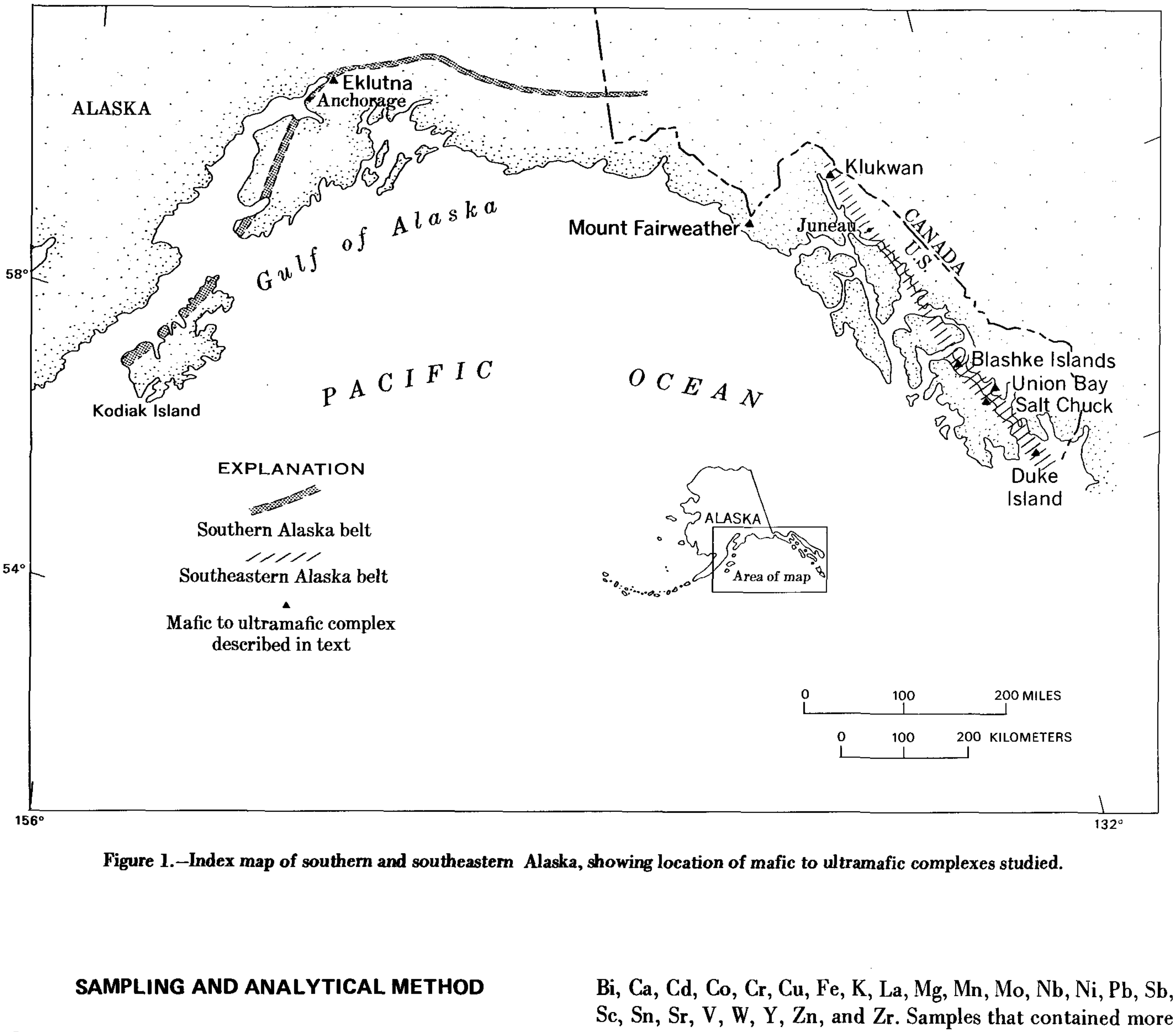

Figure 1.—Index map of southern and southeastern Alaska, showing location of mafic to ultramafic complexes studied.

SAMPLING AND ANALYTICAL METHOD

Sampling and analytical procedures for rocks collected by the authors closely follow those described by Plafker and MacKevett (1970, p. B25) for the complex at Mount Fairweather.

Rock samples of from 5 to 50 pounds were collected from surface outcrops as hand specimen samples. Sampling was directed toward selecting homogeneous rock types representative of the various phases of each complex. In areas where massive segregation of chromite and magnetite was observed, samples were selectively taken of each oxide phase. Samples were submitted as individual rock specimens weighing approximately 2 pounds or were crushed to minus 50 mesh and split, and a 2-pound fraction was sent to the analytical laboratories.

Platinum-group values were determined by the combination method of Haffty and Riley (1968).

Each sample underwent semiquantitative spectrographic analysis for the following 30 elements: Ag, As, Au, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, La, Mg, Mn, Mo, Nb, Ni, Pb, Sb, Sc, Sn, Sr, V, W, Y, Zn, and Zr. Samples that contained more than 5,000 ppm (parts per million) Cr or Ni were reanalyzed for chromium and nickel by quantitative chemical methods.

ANALYTICAL RESULTS

To date, 121 samples from the complexes have been quantitatively analyzed. The number of samples and the number of samples containing Pt, Pd, Rh, and Ir above their respective detection limits of 0.010, 0.004, 0.004, and 0.100 ppm from each complex are shown in table 1.

Table 2 lists the dominant rock types in each complex and the concentration of platinum-group metals in each type. Included are the average platinum and palladium values, the maximum values of platinum and palladium, and the maximum values of rhodium and iridium. Average values for rhodium and iridium were not calculated because too few samples contained the elements in detectable quantities.

Table 1.—*Distribution of samples from the mafic to ultramafic complexes*

Locality	Total No. samples	Platinum bearing	Palladium bearing	Rhodium bearing	Iridium bearing
Duke Island......	22	10	16	6	0
Union Bay	50	21	22	6	2
Blashke Islands...	10	8	10	0	0
Eklutna..........	16	12	12	0	0
Salt Chuck.......	6	6	6	0	0
Mount Fairweather....	7	6	6	3	0
Klukwan........	10	7	7	0	0

Table 2.—*Concentrations, in parts per million, of platinum, palladium, rhodium, and iridium*

Locality	Platinum		Palladium		Rhodium	Iridium
	Max	Avg	Max	Avg	Max	Max
Duke Island[1]...	0.200	0.037	0.140	0.033	0.010	...
Union Bay[1]....	1.600	.093	.200	.023	.062	0.215
Blashke Islands[1].	.020	.010	.020	.010	...	...
Eklutna[1].......	.100	.042	.140	.060	...	...
Salt Chuck[2]....	.160	.057	2.900	1.010	...	...
Mount Fairweather[2]..	.170	.040	.184	.036	...	...
Klukwan[2]......	.100	.046	.100	.040	...	...

[1] Dominant rock types: peridotite-dunite and hornblendite-pyroxenite.

[2] Dominant rock types: gabbro-hornblendite-pyroxenite-peridotite-dunite.

Table 3.—*Correlation of maximum platinum-palladium concentrations with host-rock type, oxide or sulfide phases, and other elements*

Locality	Associated rock type	Associated oxide or sulfide	Elements with positive correlation
Duke Island....	Hornblendite	Magnetite, chalcopyrite	Fe, V
Union Bay.....	Dunite	Chromite, magnetite	Fe
Blashke Islands.	Hornblendite	Magnetite, chalcopyrite	Fe, Ni
Eklutna.......	Peridotite	Chromite, native copper	Cu
Salt Chuck.....	Hornblendite	Bornite	Cu
Mount Fairweather..	Dunite	Chromite	Ni, Cr
Klukwan......	Pyroxenite	Magnetite, ilmenite	Fe, V

CORRELATION STUDIES

Petrographic studies of thin sections and polished sections were conducted on all chemically analyzed samples in order to correlate the highest platinum, palladium, and rhodium values with individual host-rock types and associated oxide or sulfide phases. The general rock types and mineral compositions were described by earlier workers. Correlation studies using scatter diagrams were made in order to compare platinum and palladium values within each complex with other trace and major elements. The results show a strong intercorrelation of platinum and palladium with Fe, Ni, Cr, Cu, and V, although the degree of correlation varies in different complexes. The results of these studies are listed in table 3.

CONCLUSIONS

Average platinum concentrations for the seven complexes range from 0.010 ppm (Blashke Islands) to 0.093 ppm (Union Bay—considerably below the "average" concentration of 0.20 ppm given by Vinogradov (1962). Either these Alaskan mafic to ultramafic complexes are anomalously low in platinum, or Vinogradov's figure is too high.

The same relation exists for palladium, which ranges from 0.010 ppm (Blashke Islands) to 0.060 ppm (Eklutna). Analytical values from the Salt Chuck platinum-palladium-copper mine are not considered in the preceding discussion of average values. Turekian and Wedepohl (1961) and Vinogradov (1962) estimate that "average" concentration of palladium in ultramafic rocks is 0.12 ppm, approximately four times higher than the average for the ultramafic rocks that we studied. The ultramafic complexes studied are anomalously low in palladium, as well as platinum, or the values given by Turekian and Wedepohl and by Vinogradov are high.

The similarity between the ultramafic rocks of the southeastern Alaska belt and the platiniferous complexes of the Ural Mountains, together with the anomalously high concentrations of platinum (1.60 ppm, Union Bay) and palladium (2.90 ppm, Salt Chuck), suggest that the complexes of the southeastern Alaska belt are not necessarily depleted in palladium. Therefore, the authors believe that the values given by Turekian and Wedepohl and by Vinogradov for platinum and palladium concentrations in "average" ultramafic rocks are high.

The petrographic studies and trace- and major-element correlations with platinum metals indicate that the platinum metals are closely associated with amounts of sulfide and oxide phases within the various rock types. This relation has been clearly demonstrated for the complex at Salt Chuck, where analyses of pure bornite and pure pyroxene showed 13 and 0.020 ppm Pd, respectively, and for the complex at Union Bay, where analyses of pure magnetite and pure olivine showed 30 and 0.040 ppm Pt, respectively. For each complex, the pure mineral separates were extracted from the same hand specimen.

In general, the concentration of platinum metals within each complex varies directly with olivine content. In order of decreasing platinum metal content, the rock types are dunite, peridotite, pyroxenite, and hornblendite. However, maximum values for platinum and palladium occur anomalously in hornblendites within the complexes at Duke Island, Blashke Islands, and Salt Chuck. Although the platinum-group metals are associated primarily with sulfide and oxide phases, their distribution seems to be controlled partly by the silicate phases, particularly olivine.

The platinum-group metals thus correlate with rock types, oxide and sulfide phases, and major and trace elements. However, the authors emphasize that, although the correlations are consistent within an individual complex, they differ between complexes.

Anomalous concentrations of platinum-group metals occur locally within each of the mafic to ultramafic complexes studied, but only the complexes at Union Bay and Salt Chuck are known to contain concentrations of possible economic significance.

The occurrence of anomalous concentrations of platinum-group metals within the ultramafic complexes studied, especially the one at Union Bay, shows that the Alaskan complexes resemble the platiniferous zoned ultramafic bodies of the Urals even more closely than previously recognized.

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DISTILLATION TESTS OF OIL SHALE FROM THE PHOSPHORIA FORMATION OF SOUTHWESTERN MONTANA

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Abstract.—Recovery of oil from distillation tests of 45 samples of oil shale from the Phosphoria Formation of Permian age in southwestern Montana indicates that the shale beds are too lean to be of economic interest either now or in the foreseeable future. The kerogen once present may have been converted into the oil now present in some of the oil fields of Wyoming and Montana.

The mineral evaluation and appraisal of the Federal lands and the leasing of these lands requires immediately available information on the occurrence of the leasable minerals, one of which is oil shale. The tests herein described were made as part of the collection of data on the occurrence of oil shale in southwestern Montana.

The first published reference to oil shale in southwestern Montana was made by Bowen (1918, p. 315). Although oil shale is present in beds at eight or more stratigraphic levels ranging in age from Late Devonian to Tertiary, only the deposits in the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation of Permian age are discussed in this report. Detailed descriptions, measured geologic sections, the stratigraphy, and the petrology of the units of the Phosphoria are given by Cressman (1955), McKelvey and others (1959), and Cressman and Swanson (1964). Biostratigraphy is discussed by Yochelson (1968), and mineral resources are described by Swanson (1970).

DISTILLATION TESTS

Results from samples that yielded oil on distillation tests were published by Bowen (1918, p. 318), Condit (1919, p. 24–26), Winchester (1923, p. 85–87, 90, 91), and Cressman and Swanson (1964, p. 438, 439). On the basis of those results, Swanson (1970, p. 765) discussed the oil-shale resources in the Permian rocks of southwestern Montana.

During the investigation of the western phosphate field under the direction of V. E. McKelvey beginning in 1947, stratigraphic sections of Permian rocks were measured in considerable detail, and samples were taken for analyses. Logs of the measured sections and results of the sample analyses were published as U.S. Geological Survey Circulars 209, 260, 302, 303, 326, and 375. Most of the information was consolidated by Cressman and Swanson (1964).

In November 1968, after a study of the published stratigraphic sections, a selection was made of beds in the Retort and Meade Peak Phosphatic Shale Members whose characteristics indicated that they might yield oil. Because the individual beds are thin, they were assembled into 47 groups, each group of minable thickness. Samples from the individual beds were combined in the proper proportions to make a composite sample representative of each group. The resulting samples for two of the groups were too small to be tested, but for the remaining samples the yields of oil and water were determined using the modified Fischer assay method. The samples were taken from surface trenches and are believed to be unweathered in their oil content, but little is known concerning sampling techniques best suited to the Phosphoria oil shales. Localities of the measured sections from which the samples were taken are shown in figure 1 (p. C164). Results of the tests are given in table 1. Included in the table (locality 21) are selected combined results of distillation tests of samples from Sheep Creek (Cressman and Swanson, 1964, p. 438).

RESULTS

Table 1 shows that 27 of the 45 samples tested yielded less than 1 gallon of oil per ton and only three yielded more than 5 gallons per ton. At Sliderock Mountain (loc. 3) a section 16 feet thick had an average yield of 6.4 gallons per ton; at Big Sheep Canyon (loc. 19) 16.3 feet averaged 5.8 gallons per ton and the underlying 17.9 feet averaged 8.7 gallons per ton. The richest section, at Sheep Creek (loc. 21), yielded down the section as follows:

Thickness of unit (feet)	*Yield (gal per ton)*	*Thickness of unit (feet)*	*Yield (gal per ton)*
1.0	7.0	1.8	Barren
2.2	Barren	9.1	9.05
9.1	16.13	3.2	4.70

It is concluded that the possibility is remote that the beds in the Retort and Meade Peak Phosphatic Shale Members of the

Table 1.—*Recovery of shale oil from samples of the Phosphoria Formation in southwestern Montana*

[Nos. 1–20, analyses by V. E. Shaw, U.S. Geological Survey; No. 21, analyses by U.S. Bureau Mines Petroleum and Oil-Shale Expt. Sta., Laramie, Wyo.]

No. on fig. 1	Locality	Lot No.	Reference		Member of Phosphoria Formation	Beds included in sample	Thickness of interval (feet)	Oil (gal per ton)	Water (gal per ton)
			Author and year	Page No.					
1.	Warm Springs Creek	1300	Cressman and Swanson (1964).	494	Retort Phosphatic Shale Tongue.	26–19	9.4	None	3.1
2.	Canyon Camp	1311	.....do.....	509	Retort Phosphatic Shale Member.	73–58	20.5	4.5	3.8
						56–50	10.7	(1)	(1)
3.	Sliderock Mountain	1301	.....do.....	496	......do......	63–49	16.0	6.4	5.4
4.	Hogback Mountain	1299	.....do.....	486	Retort Phosphatic Shale Tongue.	161–146	19.3	1.2	4.1
						145–131	22.8	<1.0	2.0
						130–109	21.9	1.2	4.9
						108–86	17.3	1.1	5.5
					Meade Peak Phosphatic Shale Tongue.	66–59	10.9	<1.0	2.0
5.	West Fork Madison River...	1318	.....do.....	513	Retort Phosphatic Shale Tongue.	13–1	28.4	<1.0	2.5
6.	Sawtooth Mountain.......	1241	.....do.....	444	Retort Phosphatic Shale Member.	115–100	23.2	2.1	4.8
						96–92	25.0	<1.0	3.4
7.	West Fork Blacktail Creek ...	1302	.....do.....	500	......do......	86–74	26.6	None	7.2
						72–47	33.5	3.6	8.1
					Meade Peak Phosphatic Shale Member.	21–10	10.8	<1.0	4.1
8.	Wadhams Springs.........	1246, 1247	.....do.....	450	Retort Phosphatic Shale Member.	110–97	17.1	<1.0	6.1
						96–73	20.8	(1)	(1)
					Meade Peak Phosphatic Shale Member.	34–30	14.8	<1.0	2.4
9.	Crooked Creek	1296, 1297	.....do.....	481	Retort Phosphatic Shale Member.	105–94	31.3	1.9	7.7
						93–72	37.3	2.1	8.4
					Meade Peak Phosphatic Shale Member.	52–28	13.6	None	2.4
10.	Little Sheep Creek	1294, 1295	.....do.....	476	Retort Phosphatic Shale Member.	108–99	16.7	3.1	10.8
						97–81	10.9	None	4.8
					Meade Peak Phosphatic Shale Member.	59–45	14.0	None	4.8
11.	Upper French Creek.......	1248	Klepper and others (1953).	27	D member (Klepper and others [Retort Phosphatic Shale Member]).	10–1	14.5	<1.0	7.0
12.	Kelley Gulch	1249	Cressman and Swanson (1964).	457	Retort Phosphatic Shale Member.[2]	80–62	24.6	<1.0	5.0
						55–27	24.9	<1.0	5.0
13.	South Greenstone Gulch ...	1250	Klepper and others (1953).	14	D member (Klepper and others [Retort Phosphatic Shale Member]).	37–15	41.7	<1.0	7.2
						13–5	15.6	<1.0	6.8
14.	Cave Creek..............	1257	Cressman and Swanson (1964).	473	Retort Phosphatic Shale Member.	[3]45–35	14.2	<1.0	4.8
						34–2	20.5	<1.0	4.3
15.	North Big Hole Canyon	1358	.....do.....	537	Retort Phosphatic Shale Tongue.	62–42	22.7	<1.0	4.8
						36–26	9.9	<1.0	4.2
16.	South Big Hole Canyon No. 1.	1354-A	.....do.....	528	......do......	23–16	12.9	<1.0	3.6
17.	Dalys Spur..............	1222, 1223	.....do.....	408	Retort Phosphatic Shale Member.	85–69	20.6	1.9	17.4
						68–54	20.3	2.7	14.4
						52–35	12.8	<1.0	7.2
18.	Cedar Creek	1256	.....do.....	470	......do......	58–46	29.2	<1.0	3.1
						44–1	20.7	<1.0	4.2

Table 1.—*Recovery of shale oil from samples of the Phosphoria Formation in southwestern Montana*—Continued

[Nos. 1–20, analyses by V. E. Shaw, U.S. Geological Survey; No. 21, analyses by U.S. Bureau Mines Petroleum and Oil-Shale Expt. Sta., Laramie, Wyo.]

No. on fig. 1	Locality	Lot No.	Reference		Member of Phosphoria Formation	Beds included in sample	Thickness of interval (feet)	Oil (gal per ton)	Water (gal per ton)
			Author and year	Page No.					
19.	Big Sheep Canyon.........	1224, 1225	Cressman and Swanson (1964).	414	......do......	198–195	16.3	5.8	12.0
						193–176	17.9	8.7	7.7
						172–161	16.6	4.4	4.8
						159–133	26.1	4.6	7.2
					Meade Peak Phosphatic Shale Member.	76–70	9.2	2.6	3.6
20.	Little Water Canyon........	1341	.....do.....	519	Retort Phosphatic Shale Member.	71–63	14.3	<1.0	3.4
						61–44	17.1	1.2	5.4
					Meade Peak Phosphatic Shale Member.	16–2	15.4	<1.0	10.8
21.	Sheep Creek	1234	.....do.....	438	Retort Phosphatic Shale Member.	91–89	1.0	7.0	13.4
						88	2.2	None	16.8
						87–79	9.1	16.13	12.8
						78–77	1.8	None	15.0
						76–57	9.1	9.05	12.3
						56–54	3.2	4.70	12.1

[1] Insufficient sample for analysis.
[2] Bed 80 is in Tosi Chert Member but had to be included because there was one sample for beds To-80 and Rt-79.
[3] Volcanic rocks excluded from sample and thickness.

Phosphoria in southwestern Montana contain enough shale oil to be valuable economically either now or in the foreseeable future.

Such low yields of oil on distillation test are surprising inasmuch as the black shale, phosphorite, and chert facies of the Phosphoria Formation accumulated in an area of upwelling ocean waters, an environment extremely favorable for the production of organic matter and an excellent source for oil. It may be that, although there is enough organic carbon present, there is not enough available hydrogen to produce oil. On the other hand, many geologists have believed that the Phosphoria Formation was the source of oil found in many of the oil fields of Montana and Wyoming (Sheldon, 1967). Perhaps much of the kerogen once present in the black shale was converted into oil by the heat and pressure of tectonic movement and the weight of overburden, and the oil was thus released and made available for migration into the present reservoir rocks.

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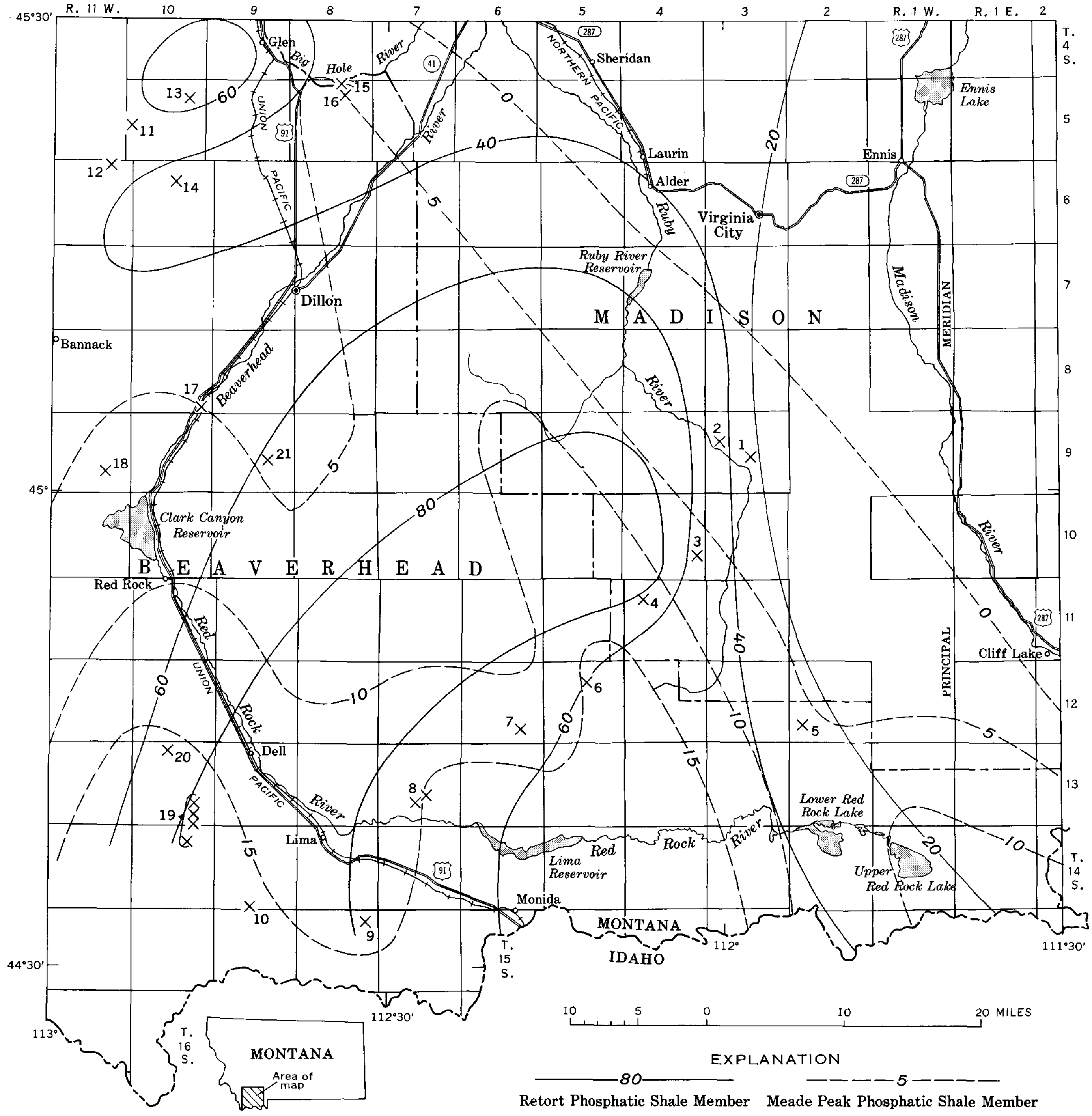
[Figure 1 on next page]



EXPLANATION

——80—— Retort Phosphatic Shale Member

— — 5 — — Meade Peak Phosphatic Shale Member

Isopachs of the Phosphoria Formation

Thicknesses in feet. From Cressman and Swanson (1964, figs. 117, 123)

×18 Locality of measured geologic section

More than one × indicates measurements at several localities. Number is that used in table 1

Base map from U.S. Geological Survey State of Montana, 1:500,000, 1966

Figure 1.—Localities of measured geologic sections of the Phosphoria Formation in southwestern Montana from which samples were taken.