# GEOLOGY OF THE RAINBOW MOUNTAIN—GULKANA GLACIER AREA, EASTERN ALASKA RANGE, WITH EMPHASIS ON UPPER PALEOZOIC STRATA

By
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GEOLOGIC REPORT 45

*Stratigraphy, structure, petrology, and sedimentology of late Paleozoic and Tertiary rocks in the Rainbow Mountain—Gulkana Glacier area*

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# GEOLOGY OF THE RAINBOW MOUNTAIN—GULKANA GLACIER AREA, EASTERN ALASKA RANGE, WITH EMPHASIS ON UPPER PALEOZOIC STRATA

By GERARD C. BOND[1]

## ABSTRACT

The Rainbow Mountain—Gulkana Glacier area is located in the eastern Alaska Range near the Richardson Highway between Phelan Creek and the upper reaches of College Glacier. The bedrock in this area is part of the complex terrane that is extensively exposed along the south flank of the eastern Alaska Range. This terrane consists of metamorphic rocks of uncertain age, upper Paleozoic volcanic and sedimentary deposits, middle Triassic greenstones, granitic intrusives of Mesozoic and Tertiary age, and Tertiary nonmarine sedimentary and volcanic deposits. Most of the work was devoted to the upper Paleozoic volcanic and sedimentary rocks to establish late Paleozoic paleogeography and paleotectonics for the eastern Alaska Range region.

The late Paleozoic and Tertiary strata are folded into discontinuous anticlines and synclines with steeply dipping limbs. Fold axes trend northwest in the western part of the area. In the eastern part of the area the folded strata appear to have been rotated counterclockwise, and the fold trend there is dominantly northeast. High-angle, reverse, and thrust faults are common throughout the area, and a major north-dipping reverse fault separates the upper Paleozoic strata from the Tertiary deposits.

The upper Paleozoic strata have been divided into two lithologic successions. The older is named the *Tetelna Complex*, and it ranges in age from middle Pennsylvanian to early Permian. The Tetelna Complex is overlain by the younger Mankomen Group, which is early to middle Permian and possibly late Permian in age. The two successions are separated by an erosional unconformity.

The Tetelna Complex consists of approximately 35 percent andesitic-basaltic lava flows, 12 percent andesitic pyroclastics, 50 percent dacitic pyroclastics, and about 3 percent rhyodacitic pyroclastics (compositions based on mineralogy). These volcanic rocks are interbedded with feldspathic and lithic sandstones and conglomerates, all of which were derived from volcanic sources. Silicified siltstones, claystones, and fossiliferous limestones also are present. The sediments of the Tetelna Complex were deposited in a moderately deep marine environment in which the principal depositional processes were submarine gravity flows and settling from suspension. Graded bedding, contorted stratification, and submarine debris flow deposits are common throughout the Complex. The nature of many of the pyroclastic deposits suggests that highly explosive Pelean and Plinian eruptions were especially common during deposition of the Tetelna strata. Grain-size and thickness changes in several of the pyroclastic deposits indicate that active vents were located a few miles west or southwest of the map area. The Tetelna Complex probably is part of an extensive succession of strata that accumulated on the flanks of a volcanic arc that was active during the late Paleozoic. The arc may have been similar to modern arcs of the western Pacific, especially those in the Kamchatka and Japanese islands.

The Mankomen Group consists of well-bedded calcarenites and calcirudites, black argillite, highly fossiliferous argillaceous calcilutites, and bryozoan bioherms. Most of the strata in the Group were deposited in shallow water at or above wave base. Volcanism in the arc had ended by the time deposition of the Mankomen Group began, and volcanic source areas were not present. The Mankomen Group probably was deposited on top of the volcanic arc after it became inactive and subsided.

## INTRODUCTION

The Rainbow Mountain—Gulkana Glacier area covers approximately 100 square miles in the eastern Alaska Range between Phelan Creek and the upper reaches of College Glacier (pl. 1). The area is readily accessible from both the Richardson Highway and an unpaved road that extends northeast from the Richardson Highway along the lower part of the Gulkana Glacier outwash plain. Most of the area is characterized by high relief, steep slopes, and relatively little vegetation, resulting in good exposures over long distances.

Mapping in the area was done during the summers of 1967, 1968, and 1972. The principal objective of the work during these summers was to map and sample in detail the late Paleozoic volcanic and sedimentary rocks that are well exposed in the higher elevations of the map area. These strata are part of an extensive belt of late Paleozoic volcanic and sedimentary rocks that extends along the south flank of the eastern Alaska Range eastward to the Canadian border. It was felt that a detailed study of these volcanic and sedimentary strata in a small area would lead to a better understanding of the nature of the rocks in the belt and might also have significant implications for regional late Paleozoic paleogeography and paleotectonics in the eastern Alaska Range. Tertiary sediments, Mesozoic intrusives, and metamorphic rocks also are present in the map area. However, these rocks were mapped and sampled only to the extent that their general character and relation to the late Paleozoic strata could be established.

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## GEOLOGIC SETTING

The Denali Fault, a major northwest-trending strike-slip fault, is the principal geologic feature in the eastern Alaska Range. In this region the fault forms the boundary between two terranes of markedly different composition (pl. 1). North of the fault the terrane consists mainly of quartzites, phyllites, schists, and greenstones that may range from early Paleozoic to Mesozoic in age (Richter and Jones, 1973, p. 409). The terrane on the south side of the fault is a complex of metamorphic rocks, ultrabasic rocks, granitic plutons, a narrow, northwest-trending belt of upper Paleozoic volcanic and sedimentary rocks, and Tertiary strata that consist of nonmarine pyroclastic rocks and fluvial sedimentary deposits.

Rocks in the map area are part of the complex terrane south of the Denali Fault. Metamorphic rocks are exposed in the northern part of the map area, and they extend northward to the Denali Fault (pl. 1). At the north end of Rainbow Mountain, the metamorphic rocks are mostly marbles, schists, and phyllites that locally contain serpentinite dikes (Hanson, 1963, p. 10-19). The age of these metamorphic rocks has not been determined; however, they lie on strike with similar metamorphic rocks that extend from the Delta River (pl. 1) westward for at least 30 miles to the Maclaren River. Near the Maclaren River the age of metamorphism is known to be Late Cretaceous (Smith and Turner, 1973, p. 23). In the headwall of Gulkana Glacier the metamorphic rocks are polymetamorphic amphibolites, peridotites, and gneisses in which the age of oldest metamorphism may be Precambrian (Ragan and Hawkins, 1966, p. 601-603).

Granitic intrusives ranging from quartz diorite to granodiorite are exposed in a belt south of the metamorphic rocks. These intrusives are probably Mesozoic in age. However, late Paleozoic and Cenozoic K-Ar ages have been reported on a few granitic intrusives of similar composition elsewhere in the eastern Alaska Range (Lanphere and Reed, 1973, p. 3775). Ragan and Hawkins (1966, p. 602) reported a K-Ar date of 149 m.y. for a gneiss at the head of Gulkana Glacier and suggested that the date indicates the time of intrusion of the plutonic rocks in that area. Small bodies of ultrabasics occur within the plutonic belt north of Rainbow Mountain along the Canwell Glacier valley (pl. 1). The age and relationship of these ultrabasics to the surrounding rocks are not known.

South of the plutonic rocks, interbedded volcanic and sedimentary rocks of upper Paleozoic age are exposed in a belt trending west to northwest (pl. 1). These deposits are in fault contact with the plutonic rocks to the north. South of the upper Paleozoic rocks are nonmarine pyroclastic and sedimentary deposits of Tertiary age, and these deposits are in fault contact with the upper Paleozoic rocks throughout the map area (pls. 1, 2).

The upper Paleozoic rocks can be traced across Phelan Creek and the Delta River into the upper Paleozoic strata mapped by Rose (1965, p. 5-8) and Stout (1965) west of the Delta River (pl. 1). There is no evidence of significant offset of the strata across the Phelan Creek—Delta River area. The Tertiary rocks seem to be confined mainly to the area east of the Delta River, although limited exposures of Tertiary deposits, too small to show on the geologic map, occur along Eureka Creek and in the area to the south.

The extent of the rocks eastward beyond the map area is not known because of the lack of detailed mapping between the head of College Glacier and Gakona Glacier. However, reconnaissance mapping by Moffit (1954, pl. 7) shows that Tertiary strata immediately east of the Gakona Glacier lie directly on strike with the upper Paleozoic rocks exposed along College Creek. In addition, a granitic pluton is exposed southeast of College Glacier near upper Fish Creek (pl. 1). This pluton is in intrusive contact with what appears to be the upper part of the Mankomen Group. Thus, the outcrop pattern in the map area does not appear to continue eastward beyond the headwall of College Glacier.

## STRATIGRAPHY

### UPPER PALEOZOIC ROCKS

The earliest stratigraphic studies of the upper Paleozoic rocks in the map area were made by Mendenhall (1900, p. 313) and Moffit (1912, p. 27-29; 1954, p. 94-118) during their reconnaissance mapping in the central and eastern Alaska Range. These authors noted the abundance of volcanics in the rocks exposed north of Phelan Creek. Moffit (1912, p. 27) suggested that the strata there were correlative with the Chisna Formation of Carboniferous age (Mendenhall, 1905, p. 33-35). The Chisna Formation is exposed about 15 miles east of the map area in the headwaters of the Chistochina River (pl. 1). Later, Moffit (1954, p. 106, pl. 7) reported Permian fossils from rocks near The Hoodoos (map unit $Pml_2$, pl. 2) and correlated this small outcrop with the Permian Mankomen Formation (Mendenhall, 1905, p. 40-46) exposed east of the Middle Fork of the Chistochina River (pl. 1).

Hanson (1963, p. 19-31) and Rowett (1969, p. 10-24) completed the first detailed stratigraphic studies of the upper Paleozoic rocks in the northwestern part of the map area. These authors divided the volcanic and volcanic-derived sedimentary rocks between McCallum Creek, Canwell Glacier, and the Richardson Highway into the Rainbow Mountain sequence and the McCallum Creek sequence (fig. 1). On the basis of scattered fossil collections from these strata, the Rainbow Mountain sequence was considered to be middle Pennsylvanian (Atokan-Desmoinesian?) in age and the McCallum Creek sequence was placed in the lower(?) Permian (Wheeler, in Hanson, 1963, p. 50-52; Unklesbay and Pauken, 1966; Rowett, 1969, p. 17-24). However, in this report and in Bond (1969), the author has shown that part of the Rainbow Mountain sequence at the south end of Rainbow Ridge is lower Permian in age (compare fig. 1 with pl. 2). In addition, Hanson stated that the two sequences are nearly identical lithologically. It is clear that the Rainbow Mountain sequence is not a valid time stratigraphic unit, nor are the two sequences sufficiently distinct lithologically to qualify as valid lithologic map units. Consequently, the stratigraphic nomenclature proposed by Hanson and Rowett should be discontinued.

The area to the east, between McCallum Creek and College Glacier, was previously mapped by the author (Bond, 1965). He found that the strata described by Hanson extend into this area and are overlain by a thick succession of lower Permian limestones and black argillites. In marked contrast to the underlying strata, these limestones and argillites contain no erupted volcanic material.

In this report, the author has divided the upper Paleozoic strata in the map area into two lithologic successions which, although variable within themselves, are significantly distinct from each other. The upper of these two successions includes the limestones and black argillites exposed east of McCallum Creek that were found to overlie Hanson's stratigraphic divisions. This succession includes map units $Pml_1$, $Pma_1$, $Pml_2$, $Pma_2$, and Pmal (pl. 2). It is now clear that these map units are part of the Mankomen Group as defined by Richter and Dutro (in press), and are designated as such on the geologic maps (pls. 1, 2).

The lower succession includes the diverse volcanic and volcanic-derived sediments of upper Paleozoic age that underlie the Mankomen Group. All of the map units Pwg to Pbm (pl. 2) are included in this succession. The top of the lower succession is defined as the top of the stratigraphically highest volcanic deposit, unit Pbm.

Recent work in the eastern Alaska Range has shown that these pre-Mankomen strata are part of an extensive upper Paleozoic volcanogenic complex. This complex is exposed along the south flank of the central and eastern Alaska Range from a few miles west of the Delta River (pl. 2) to and probably beyond the Canadian border (Rose, 1965, p. 5-8; Richter and Jones, 1973, p. 412; Bond, 1973). Richter and Dutro (in press) recently have referred to the volcanic succession as the Tetelna Volcanics, a name first used by Mendenhall (1905, p. 36-38) for a succession of late Paleozoic volcanic rocks exposed near Mentasta Pass, about 60 miles southeast of the map area. Their usage will be followed here except that the word *Complex* will be used in place of *volcanics*. Use of *volcanics* is somewhat misleading because, although the Tetelna strata are composed largely of volcanics, the strata also contain a significant amount of nonvolcanic rocks including fossiliferous limestones, claystones, siltstones, conglomerates, and shallow intrusives (pl. 3). The term *complex* is defined in the American Code of Stratigraphic Nomenclature (1972) as "... a mass of rock composed of diverse types of any class or classes...", and the term therefore is more appropriate than the restrictive *volcanics*.

In previous papers by the author, the volcanogenic complex has been called the Phelan Creek formation and the Delta River sequence, and the upper succession of limestone and black shale was named the Gulkana Glacier formation (Bond, 1969, 1973). These were local, informal names used primarily for purposes of description at a time when the regional stratigraphic relations in the eastern Alaska Range were poorly understood. Use of these informal names is now discontinued.

## TETELNA COMPLEX

The Tetelna Complex in the map area consists of andesitic to basaltic flows and andesitic to rhyodacitic pyroclastics interbedded with tuffaceous claystones and siltstones, volcanic-derived sandstones and conglomerates, and a few discontinuous lenses of fossiliferous limestones. The total exposed thickness of the Complex in the map area, based on a composite section (pl. 3), is approximately 8,500 feet. These strata have been divided into several informal map units (pl. 2), each of which is characterized by distinct sedimentary and/or volcanic rock types (see Appendixes I and II for detailed descriptions of these units). Pyroclastic materials, which are abundant in the Tetelna Complex, were especially useful in correlating these map units across faults and covered intervals. The pyroclastics were correlated using several criteria, the most important of which are presence or absence of quartz and K-feldspar phenocrysts, phenocryst composition of pumice, abundance and types of lithic clasts, and internal layering.

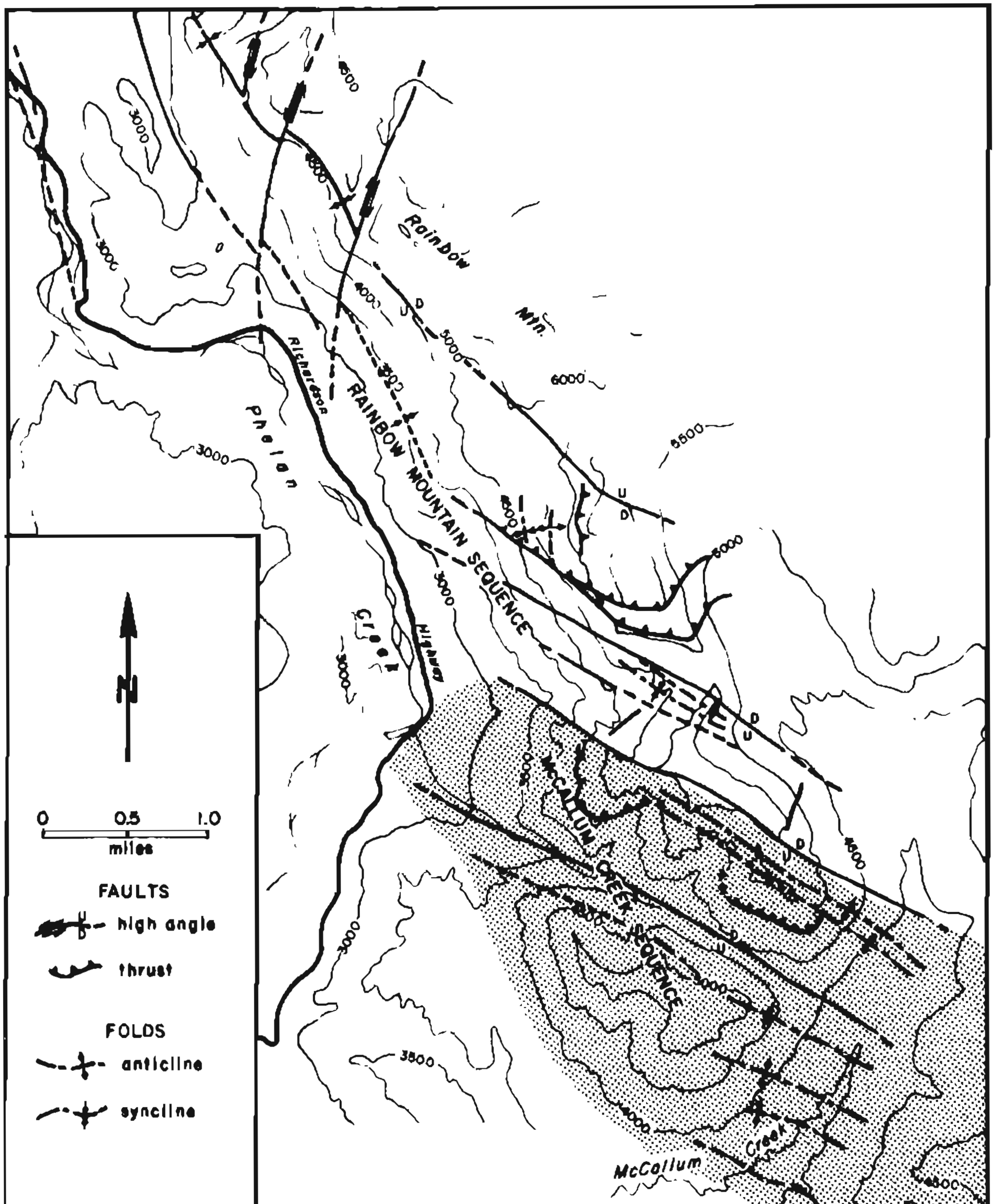


FIGURE 1.—Location of the Rainbow Mountain and McCallum Creek sequences in the Rainbow Mountain area.

However, because of the complex structure and large covered intervals on Rainbow Mountain, the correlations of map units in the lower part of the Complex (units below Pov) are tentative. Also, the contacts between some of the units in this part of the section are faulted (see the composite section, pl. 3), and the thicknesses of these units are only approximate. On the other hand, the upper part of the Complex (units Pov to Pbm) is much better exposed, and stratigraphic relations in these strata are well established.

The age of strata in the Complex has been reported by Gilbertson (1969, p. 27-31), Rowett (1969, p. 17-24), and Rowett and Timmer (1973, p. 3-4). The oldest dated strata are in map unit IPsc. A fusilinid-bearing limestone was collected from this map unit at the south end of Rainbow Ridge, about 1/2 mile due west of measured section 20 (pl. 2). J.W. Skinner of Humble Oil Company identified these fusulinids as *Fusulinella* sp. of Atokan or Desmoinesian (Middle Pennsylvanian) age (Skinner, personal communication, 1969). A large collection of fossils has been made from map unit Pkr in a black limey bed exposed at milepost 212 on the Richardson Highway in measured section 24 (pl. 2, pl. 3). Rowett and Timmer (1973, p. 3-4) have confirmed a lower-middle Pennsylvanian (post-Morrow—pre-Missouri) age for this fossil assemblage. Higher in the section, map units Pmr and Pfc contain fusulinids of lower Wolfcampian (lowest Permian) age (Gilbertson, 1969, p. 27-28). Most of the fossil collections from these two units were obtained from strata in measured sections 6, 7, 10, 12-14, and 17 (pl. 2). Although only a few horizons in the stratigraphic section can be dated, it appears that the Tetelna Complex in the map area ranges in age from at least middle Pennsylvanian to lower Permian. There are too few data to accurately locate the Pennsylvanian-Permian boundary, although it must lie between map units Pkr and Pmr. For convenience, the boundary is placed at the top of map unit Prh because this unit is a distinctive dacitic pyroclastic deposit (Appendix I) that can easily be traced across the map area. Stout (1965) described a similar quartz-bearing deposit (his map unit dp) exposed near the mouth of Ann Creek, about 4 miles north of Rainey Creek (pl. 1). This deposit may be equivalent to map unit Prh.

The base of the Tetelna Complex has never been seen either in the map area or in other parts of the eastern Alaska Range. Consequently, rocks older than middle Pennsylvanian may be present in the Complex. Also, there is as yet no conclusive evidence indicating the type of terrane on which the Complex was deposited. Richter and Jones (1973, p. 412) suggested that the Complex may rest on oceanic crust, whereas Bond (1973) postulated that the Complex may have been deposited on continental crust, a part of which is now exposed in the metamorphic terrane northeast of the Denali Fault.

## MANKOMEN GROUP

A middle Wolfcampian age for the lower part of the Mankomen Group (unit $Pml_1$) is well established by fusulinids collected from measured sections 4 and 5 (Gilbertson, 1969, p. 28-29). A conodont found in a limestone sample from unit $Plm_2$ near The Hoodoos (pl. 2) was identified as *Lonchodina* sp. aff. *L. festiva* Bender and Stoppel (F.H. Behnken, personal communication, Univ. Wisc., 1969). The range of this conodont is not well known, but it probably is middle to upper Permian in age.

The contact between the Tetelna Complex and the Mankomen Group is exposed in measured sections 4 and 5 (pl. 2). The contact may also be present above section 1, although the rocks there are severely deformed. Both faunal and lithologic evidence indicate that the contact is an erosional unconformity. In both sections 4 and 5, lenses of feldspathic sandstone, rarely more than 3 feet thick, occur sporadically at the base of the Mankomen Group. These lenses contain rounded lithic fragments, some of which are identical in texture and apparently in composition to the underlying lapilli tuff (unit Pbm). The fragments must be local concentrations of sand eroded from the underlying lapilli tuff prior to deposition of the overlying Mankomen limestones.

An unconformity is further indicated because map units Pmr, Pfc, and Pmc of the Tetelna Complex contain the fusulinid genus *Thompsonella*, whereas the limestones of the Mankomen Group immediately above unit Pbm in sections 4 and 5 contain *Eoparafusulina* and *Schwagerina* and lack the genus *Thompsonella* (Gilbertson, 1969, p. 28-29). The occurrence of *Thompsonella* in the upper units of the Tetelna Complex (Pfc and Pmc) indicates that these members are correlative with zone A of the McCloud Formation of lower Permian age in California. The occurrence of *Eoparafusulina* and *Schwagerina*, together with the absence of *Thompsonella* in the lower part of the Mankomen Group, is evidence that the strata immediately above unit Pbm are equivalent in age to zone E of the McCloud Formation. As is shown in a following section, unit Pbm was deposited during a single, major volcanic eruption that may have lasted no more than a few months. The evidence, therefore, suggests that a faunal gap corresponding to zones B, C, and D of the McCloud Formation occurs at the contact between the Tetelna Complex and the Mankomen Group.

Recently, Rowett (1969, p. 26-29) completed a study of the corals in the upper Paleozoic strata of the map area. He established 11 coral zones that he thought would be useful for regional correlation. His uppermost four coral zones (*Canina petoczi* to *Durhamina alaskensis*) are from strata placed in the Mankomen Group in this report. However, by comparing figure 2 with plate 2, it can be seen that at least five of his other coral zones occur within map unit Pfc in the Tetelna Complex. The five zones are *Heritschioides summitensis*, at location

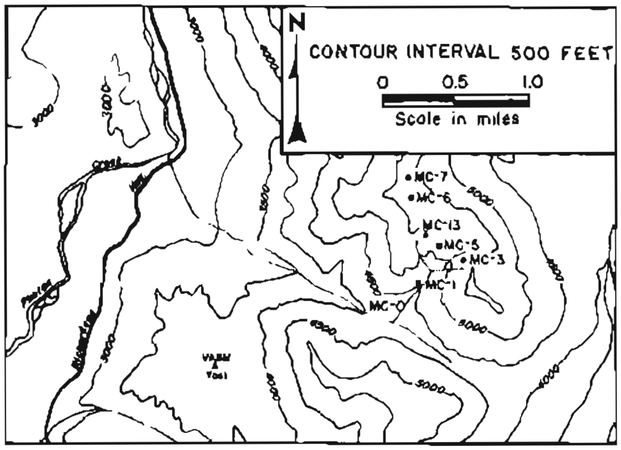


FIGURE 2.—Location of coral zones in the upper part of the Tetelna Complex.

MC-6; *Timania rainbowensis* at location MC-13; *Syringopora katoi* at location MC-5; *Bothrophylium* cf. *B. pseudoconicum* at location MC-3; and *Timania* sp. A at location MC-0 (fig. 2). Evidently, Rowett was not aware that map unit Pfc is repeated by faulting, and he assumed that each of the limestone outcrops that yielded these corals was in a different stratigraphic unit. The corals in the five zones probably are species from different communities within the same limestone deposit in map unit Pfc. Clearly, a complete restudy of the lower five coral "zones" is needed. However, the uppermost four zones in the Mankomen Group appear to be valid zones that should be useful for correlation.

## NIKOLAI GREENSTONE

Three small exposures of greenstone (map unit TRn) occur south of College Creek (pl. 2). These rocks are mainly greenish black to reddish, fine-grained amygdaloidal basalts. From a distance, vaguely defined layers several feet thick can be seen within parts of the greenstone. These layers probably are individual flows. The greenstones strongly resemble fine-grained amygdaloidal greenstones exposed east and west of the Middle Fork of the Chistochina River (pl. 1 and Bond, unpublished field data, 1973). The greenstones in that area are middle Triassic in age (Richter and Jones, 1973, p. 412-414; Matteson, 1973); and Richter (personal communication, 1973) has correlated them with the Triassic Nikolai Greenstone exposed in the southern Wrangell Mountains (Mackevett, 1964). Richter (1967, p. 7) and Matteson (1973) reported that the contact of the greenstone sequence near the Chistochina River with the underlying Mankomen Formation is a slight angular unconformity. Unfortunately, the greenstones in the map area are separated from the Mankomen Formation by faults and the nature of the contact cannot be compared with that to the east. However, the similarity of the greenstones in the map area with those described by Richter and Matteson suggests that they may be part of the same flow complex. Accordingly, the greenstones in the map area are tentatively correlated with the Nikolai Greenstone. Clearly, additional work on these volcanics, particularly chemical analyses, is necessary before such a correlation can be confirmed.

A short distance east of the Delta River, similar greenstones apparently overlie the Mankomen Formation (pl. 1), although the contact is not exposed. Since these greenstones appear to occupy the same stratigraphic position as the Triassic greenstones east and west of the Middle Fork of the Chistochina, they are also tentatively correlated with the Nikolai Greenstone.

## TERTIARY DEPOSITS

### MAP UNIT Tv

The oldest Tertiary unit in the map area is a light-tan rhyodacitic lapilli tuff exposed south of College Creek (pl. 2). This deposit appears to be in fault contact with the pre-Tertiary rocks, although it may unconformably overlie the southernmost exposure of the Nikolai Greenstone (pl. 2). The pyroclastic deposit is unconformably overlain by a coarse conglomerate, map unit $Ts_1$. The total thickness of the rhyodacite tuff is unknown, but the maximum exposed thickness probably exceeds 600 feet. The pyroclastic material consists mainly of crystals, glass shards, and pumice, but large amounts of lapilli-sized lithic debris are present locally. A limited petrographic study of this tuff indicates that it is welded, at least in part. The deposit is characteristically well stratified, and the layers range from a few inches to several feet in thickness. A crude columnar jointing is visible in a few outcrops. Rose (1967, p. 13) reported the presence of a similar tuff just east of Gakona Glacier, and this deposit also is included in map unit Tv (pl. 1).

The following petrographic description was given by the author (1965) for two samples collected south of College Creek.

> Two tuff specimens examined contain approximately equal amounts of crystal fragments and glass with minor amounts of lithic fragments. Crystal fragments consist of sanidine, orthoclase (positive potassium feldspar strain, 2V $70^{\circ}$), plagioclase (An 40), quartz, and biotite. Sanidine is usually poikilitic, with plagioclase, biotite, and apatite inclusions. Plagioclase commonly exhibits fine albite or combined Carlsbad and albite twinning and less commonly normal oscillatory zoning. The glass fraction consists of clear glass shards embedded in a matrix of isotropic brown silica dust. Larger shards exhibit perlitic fractures and contain phenocrysts of biotite, plagioclase, sanidine, and orthoclase. Lithic fragments include siltstone, a possible altered diorite fragment, a fragment composed of epidote and serpentine, and several fragments of andesite (dacite?) with highly devitrified matrices. Of the latter, one fragment contains phenocrysts of fresh biotite, sanidine, ortho-

clase, plagioclase, and a faint suggestion of a welded glass fraction.

Grain shape and size vary considerably. Biotite and plagioclase grains are euhedral and the latter are commonly fractured along one or more edges. Quartz and potassium feldspar are subhedral to anhedral, embayed, and in many cases have fractured outer edges. Lithic fragments are rounded to subrounded. Glass shards are irregularly shaped but generally elongated in one direction. Grain size of lithic, crystal, and shard fragments ranges from 0.1 to 3 millimeters.

Welding and compaction have affected both shards and small biotite grains. Elongated shards are aligned over short distances and in some cases partially fused. Many shards have been molded around sharp edges of crystal fragments. Edges of larger shards typically are frayed and drawn out parallel to surrounding smaller shards. Small biotite grains are aligned with the shards and in several places severely warped or broken.

A K-Ar date of 49 m.y. (Eocene-Oligocene) was determined for a sample of this deposit collected about 1 mile southeast of The Hoodoos (D.L. Turner, University of Alaska, personal communication, 1973).

## MAP UNIT $Ts_1$

The rhyodacitic lapilli tuff is overlain, probably unconformably, by a coarse conglomerate shown on the map (pl. 2) as unit $Ts_1$. An abundance of dark-colored clasts in this deposit gives it a distinctive black color when viewed from a distance. A few thin white tuffs are interbedded with the conglomerate. in the southern exposures of the deposit, indicating that volcanism was contemporaneous with deposition of the gravels. In exposures along the ridge immediately south of College Creek (pl. 2), clasts in this deposit are as much as 3 feet wide. The grain size appears to decrease to fine pebbles southward, suggesting that the conglomeratic debris were derived from the north. The coarse grain size of this deposit, together with the abrupt decrease in grain size southward, suggests that it is a fanglomerate deposited near the source area on a steeply sloping surface. Many of the clasts in the conglomerate obviously were derived from the older map units in the area. Fragments of the rhyodacitic lapilli tuff, Nikolai Greenstone, Mankomen Formation, and the Tetelna Complex are abundant. Less abundant clasts include quartz diorite and a variety of metamorphic rocks.

The age of this conglomerate is uncertain. It clearly is younger than the rhyodacitic lapilli tuff. However, the relationship of the conglomerate to map unit $Ts_2$, late Miocene to early Pliocene in age, is obscured by faulting. The deposit probably is older than map unit $Ts_2$ because the conglomerate lies directly on the rhyodacitic lapilli tuff. The conglomerate is tentatively considered to be post-Eocene to pre-Miocene in age.

## MAP UNIT $Ts_2$

Map unit $Ts_2$ (pl. 2) consists of interbedded light-colored conglomerates and sandstones, gray siltstones and claystones, and a few thin white ash layers. The conglomerates and sandstones tend to be lenticular and probably are channel deposits laid down by braided streams. The siltstones and claystones typically contain organic debris, much of which consists of carbonized leaf impressions and parts of tree trunks. The ash layers are siliceous, probably rhyodacitic to rhyolitic in composition. A cursory study of the clasts in the conglomerates indicates that granitic and metamorphic rock types are especially abundant. Some of the conglomerates exposed about 1 mile north of the word *Creek* in Phelan Creek (pl. 2) contain black argillite fragments. A few of these black clasts bear upper Paleozoic bryozoa and brachiopods, and the clasts probably were derived from black argillite in the Mankomen Group. Deposits of this unit exposed south of College Creek contain distinctive white quartzite clasts along with granitic and metamorphic rock fragments. Obviously, this map unit was derived from one or more source areas that were composed of a variety of rock types. Cross bedding, ripple marks, pebble imbrication, and other directional sedimentary structures are abundant in these gravels. A study of these sedimentary structures and a compositional analysis of the diverse clasts in the gravels could easily be undertaken, and might provide interesting data on Tertiary source areas and drainage patterns.

A K-Ar date of 5 m.y. (late Miocene to early Pliocene) was obtained from a sample of a white ash layer collected in a small gully about 1/2 mile south of The Hoodoos (pl. 2; D.L. Turner, University of Alaska, personal communication, 1973). In addition, plant fossils collected from exposures of gray siltstone along McCallum Creek were found to be Miocene to Pliocene in age (Florence R. Weber, USGS, personal communication, 1973). Probably, most of map unit $Ts_2$ is late Tertiary in age.

# STRUCTURE OF UPPER PALEOZOIC AND TERTIARY STRATA

## FOLDING

The upper Paleozoic strata in the map area have been folded into anticlines and synclines, most of which have steeply dipping limbs. Some of the folds have vertical axial planes; however, most of them are slightly overturned to the south, and the axial planes dip 70 to 80 degrees northwestward. Most of these overturned folds occur in the northwest part of the map area between McCallum Creek and the south end of Rainbow Ridge (pl. 2). From McCallum Creek northwestward to the south end of Rainbow Ridge, folds in the upper Paleozoic strata trend mostly northwest. Farther to the northwest, on Rainbow Ridge itself, fold troughs and crests are not exposed, but reversals in dip suggesting folding occur across faults and covered intervals (pl. 2). The trend of these inferred folds appears to be northwestward also. East of Gulkana Glacier, along the College Glacier valley, the strike of bedding and the fold trend in the upper Paleozoic rocks have changed to northeast, roughly parallel to the valley itself (pl. 2). A surprising deviation from the northeast direction of folding occurs in this area near The Hoodoos, where fold axes in limestones and argillites of the Mankomen Group trend almost due north (pl. 2).

The Tertiary deposits also are folded, but the limbs generally are not as steeply dipping as those in the upper Paleozoic strata. Folds of the Tertiary deposits have not been mapped in detail, but fold axes appear to trend northwestward, essentially parallel to the fold trends in the upper Paleozoic deposits.

## FAULTING

The pattern of faulting within the map area changes significantly across the Gulkana River; consequently, the faults west and northwest of the Gulkana River valley are discussed separately from those east of the valley. Northwest of the valley, from the north end of Rainbow Ridge to the Gulkana River, four sets of faults can be distinguished: (1) a north- to N. 20° E.-trending set with nearly vertical planes along which the slip has been mostly lateral; (2) a set trending about N. 50° W. with nearly vertical planes; (3) a set of reverse faults with fault planes dipping northeast at an angle of about 60 degrees; and (4) thrust faults with fault planes nearly horizontal (pl. 2). With the exception of the reverse faults, these are essentially the same sets of faults described by Hanson (1963, p. 59-65) for the Rainbow Ridge area. Hanson (1963, p. 64) concluded that the lateral slip along the north to N. 20° E. trending faults is left lateral on some and right lateral on others. In addition, mapping by the author in the Tertiary deposits about 2 miles east of McCallum Creek (unit $Ts_2$) shows that the vertical axial plane of an anticline in the Tertiary sediments is offset by about 500 feet of left lateral slip along a north-trending fault (pl. 2).

On the northwest-trending faults, the vertical stratigraphic offset may reach as much as 3,000 feet (estimated from cross sections, pl. 2). Whether this displacement is due to vertical or lateral slip is unclear. However, more than 2 or 3 miles of lateral slip on these faults seems unlikely because facies patterns in the upper Paleozoic strata can be matched across the faults. As is shown in a following section, lithofacies within the upper Paleozoic strata change laterally within such short distances that more than 2 or 3 miles of lateral slip would have juxtaposed markedly different lithologies within coeval strata.

The north-dipping reverse faults are exposed along the southwest side of Rainbow Ridge, north of Phelan Creek, between West Gulkana and College Glaciers, and along the north wall of the College Glacier valley (pl. 2). These reverse faults cut the plutonic rocks, the upper Paleozoic strata, and the Tertiary deposits. The most extensive of these reverse faults is the one separating the Tertiary and upper Paleozoic deposits along the southwest part of the map area (pl. 2). This fault is inferred primarily from the trend of the Tertiary-upper Paleozoic contact in the Gulkana River valley. The Tertiary-upper Paleozoic contact bends northward into the valley on the west side, a pattern suggesting the trace of a north-dipping fault plane. The bend also could indicate an unconformable contact between the Tertiary gravels and an irregular pre-Tertiary erosion surface. However, the Tertiary gravels exposed along the west wall of the Gulkana River valley contain only a few clasts of lithologies that could have been derived by erosion of the upper Paleozoic rocks in the immediate area. Furthermore, along the first ridge north of Phelan Creek where the reverse fault is shown as a solid line (pl. 2), the Tertiary deposits dip 20 degrees north directly into or below the upper Paleozoic strata. Also, just below the fault in this same area, the Tertiary strata are sheared and oxidized—as would be expected in a fault zone.

Thrust faults with nearly flat planes are exposed on the south side of the ridge immediately south of the west fork of McCallum Creek (pl. 2). Offset along these faults is confined to the upper Paleozoic strata. Juxtaposition of stratigraphic units along these faults indicates that the upper plates moved southward (pl. 2). The maximum stratigraphic displacement along the thrusts is not more than a few hundred feet.

In the area east of Gulkana River and south of College Creek, the faults can be grouped into two sets: (1) faults with steeply dipping planes trending approximately N. 60° E.; and (2) faults with steeply dipping planes trending approximately N. 40° W. (pl. 2). Whether lateral or vertical slip (or both) has occurred along these two sets of faults is not clear. However, the bend in folding in the upper Paleozoic strata from N. 60° E. to north at The Hoodoos could be due to drag caused by left lateral slip along the large northwest-trending fault separating map units Tv and $Ts_2$ (pl. 2). Maximum vertical stratigraphic offset across these faults is difficult to calculate because the thickness of the Triassic and Tertiary deposits is unknown. However, since most of the Mankomen Group and the Nikolai Greenstone has been faulted out along some of the northeast-trending faults (pl. 2), vertical stratigraphic offset may be on the order of a few thousand feet.

A northeast-trending fault has been placed along the Gulkana River (pl. 2) to account for the stratigraphic and structural differences in the areas east and west of the Gulkana River valley. In particular, the Nikolai Greenstone and the upper part of the Mankomen Group (units $Pml_2$, $Pma_2$, and Pmal, pl. 2) are exposed east of the Gulkana River, but are not present anywhere west of the river. The absence of these rocks west of the river suggests that the pre-Tertiary strata west of the valley have been uplifted more than pre-Tertiary strata east of the valley. The differential movement can be accounted for by assuming that the western area is the upthrown side of a vertical fault concealed beneath the Gulkana River valley deposits (pl. 2). Also, movement along such a fault could be responsible for the marked change in the strike of bedding and trend of faulting across the Gulkana River valley. It is interesting to note that if the upper Paleozoic, Triassic, and Tertiary strata east of Gulkana River were rotated about 30 degrees clockwise, both the strike of bedding and trends of faulting in these units would become parallel to the trends of bedding and faulting west of the Gulkana River (see pl. 2); also, the N. 40° W.- and N. 60° E.- trending sets of faults east of the river would become parallel to the north-to-N. 20° E. and N. 50° W. sets, respectively, west of the river. Thus, it appears likely that the Gulkana River valley has been cut into a major northeast-trending fault zone. A glance at plate 1 shows that the Gakona and Chistochina Glacier drainages also are in northeast-trending valleys. Perhaps these valleys also mark major northeast-trending fault zones.

## AGES OF FOLDING AND FAULTING

The structural and stratigraphic relations in the map area permit a tentative reconstruction of deformation events. The late Miocene to early Pliocene age of the upper Tertiary sediments (unit $Ts_2$, pl. 2) clearly indicates a post-Miocene age for the folding of these deposits. Also, the rhyodacitic tuff of Eocene to Oligocene age is not as severely folded as the upper Paleozoic strata. This suggests that the tight folds and thrust faults in the pre-Tertiary rocks of the map area were produced during pre-Eocene-Oligocene time. North of Phelan Creek, the three north-trending faults in the upper Tertiary deposits and the reverse fault separating the Tertiary and Permian strata are most likely post-Miocene in age. This relation suggests that all of the other N- to N 20° E-trending faults and the reverse faults in the map area are post-Miocene in age. In the ridges north of McCallum Creek, the fold axes in the upper Paleozoic strata are cut by the N. 50° W.-trending fault set. Therefore, this fault set must postdate the folding of the pre-Tertiary rocks (pl. 2).

Assuming that the faults east of the Gulkana River were parallel to those west of the river prior to the rotation postulated above, then the fault southeast of The Hoodoos that separates map unit $Ts_2$ from unit Tv would have been part of the N. 50° W.-trending set west of the Gulkana River. It is clear from the map (pl. 2) that this fault southeast of The Hoodoos is post-Miocene in age. This suggests a very speculative post-Miocene age for the N. 50° W.-trending fault set in the map area. Finally, assuming that the strata east of the Gulkana River have been rotated clockwise by movement along a fault in the Gulkana River valley, this fault must have been the most recently active one in the map area.

In summary, the sequence of folding and faulting in the map area would appear to be: (1) prior to the Eocene, a period of deformation produced the folds in the pre-Tertiary rocks; (2) a second period of folding occurred after Miocene or early Pliocene time. Possibly this second period of folding steepened and overturned the earlier folds in the pre-Tertiary rocks and produced the small thrust faults; (3) also in post-Miocene time, deformation produced the reverse faults, the north-to-N. 20° E.-trending fault set, and possibly the N. 50° W.-trending set; and (4) the most recent deformation in the map area may have occurred along the inferred fault in the Gulkana River valley, and may have caused counterclockwise rotation of the block east of the Gulkana River.

# DETAILED DISCUSSION OF THE UPPER PALEOZOIC ROCKS

## METAMORPHISM

Hanson (1963, p. 21-32) reported that the mineralogy in most of the upper Paleozoic strata is largely secondary. The secondary mineralization is especially widespread in the volcanic rocks of the Tetelna Complex. Nearly all of the original mafic minerals have been replaced by chloritic minerals (mostly penninite), epidote, and calcite. The original glassy matrix of pyroclastic rocks is either replaced by chloritelike material or has recrystallized to a mosaic of microcrystalline feldspar and quartz. Relict shards were recognized in only a few samples. Feldspar phenocrysts are mostly albitic in composition ($An_{0-10}$, determined by indexes of refraction on cleavage pieces and by microprobe analysis). However, these secondary minerals developed without appreciable shearing, since most of the clastic textures in the sediments are partly or completely preserved. Also, textures in the volcanic deposits and in the lithic fragments in sediments are generally still visible. Even pumiceous textures are remarkably well preserved, and usually can be recognized, especially if observed on wetted, polished surfaces as suggested by Fiske (1969, p. 6). The limestones in both the Tetelna Complex and Mankomen strata are recrystallized to a certain extent, but the original textures still are visible, and most of the skeletal structures in fossils can be recognized.

The secondary mineralogy, together with the lack of schistose structure, generally has been taken to indicate a greenschist-facies metamorphism that was produced by a thermal event. However, it should be noted that the mineralogy and texture of these rocks, particularly those in the Tetelna Complex, are not unlike the mineralogy and textures of rocks of the spilite-keratophyre association. The abundance of albitic feldspar is particularly indicative of a soda-rich rock suite. Significantly, most of the feldspar is relatively free of inclusions such as epidote and calcite. Such inclusions would be abundant if the albitic plagioclase was entirely the result of decalcification of the feldspar during greenschist-facies metamorphism. On the other hand, albitic plagioclase free of secondary minerals is characteristic of spilitic and keratophyric rocks. A few chemical analyses of these rocks have been made (table 1); they indicate abnormally high sodic compositions similar to those of spilite and keratophyre rock types. Although more chemical data are needed to confirm the presence of spilitic-to-keratophyric rock types in the upper Paleozoic volcanics, the data presently available raise some question as to the degree of true greenschist-facies metamorphism in the upper Paleozoic rocks. In any case, the original stratification and textures of the sedimentary and volcanic rocks are sufficiently well preserved that stratigraphic and sedimentologic studies are not severely hampered by the degree of metamorphism in these rocks.

## TETELNA COMPLEX

This project was devoted largely to a study of the lithology and sedimentation of deposits in the Tetelna Complex because, although rocks of this type are common in the eastern Alaska Range and in parts of Canada (Bond, 1973), their characteristics and genesis rarely have been examined in detail. The individual lithologies in the Complex are not unique sedimentary deposits; rather, the unusual feature of these strata is the complex stratigraphic relations between highly diversified rock types. This phenomenon is especially well illustrated by the common interstratification of calcarenites and calcirudites, bioherms and biostromes, coarse-grained pyroclastic materials, lava flows, and marine sandstones and conglomerates with distinct graded bedding. These lithologies were observed in the field to change vertically and laterally from one to the other, in some places within a distance of less than 100 feet. In the following sections, special emphasis is given to the composition of the volcanic deposits, types of volcanic eruptions, depositional environments, manner in which the pyroclastic and sedimentary rocks were deposited, and a reconstruction of the late Paleozoic paleogeography and geologic history.

### COMPOSITION OF THE VOLCANIC ROCKS

Compositional names are difficult to apply accurately to the volcanics because of the widespread occurrence of secondary minerals in these rocks and a lack of enough chemical analyses. The problem is further complicated by the possibility, discussed in a previous section, that some, and perhaps all, of the rocks are abnormally sodic. The main purpose of this section is to show that the volcanic rocks of the Complex are mostly siliceous pyroclastic deposits which, on the basis of mineralogy, are predominately andesitic (keratophyric?) to dacitic (quartz keratophyric?).

Both flows and pyroclastic deposits are present in the Complex (pl. 3), and the composition of the volcanics ranges from basaltic or andesitic to rhyodacitic. The basaltic-andesitic flows are composed of albitic plagioclase and mafic (amphibole?) phenocrysts in a fine-grained matrix of plagioclase microlites (albite?) and fine-grained chloritelike minerals (originally glass?). The microlites usually show a distinct trachytic texture. Potassium feldspar is absent (determined by staining sodium cobaltinitrite). The andesitic pyroclastics contain albitic plagioclase, large amounts of pumice (20 to 60 percent), and variable amounts of lithic clasts and recrystallized glassy matrix. Quartz and potassium feldspar are absent. The mineralogy does not exclude a

TABLE 1. *Chemical analyses of volcanic rocks in the Tetelna Complex.*

| | Fine-grained volcanic clasts in lithic sandstones from map unit Pmc[1] | | Flow breccia from map unit Pwf[2] | | |
|---|---|---|---|---|---|
| Compound | a | b | a | b | c |
| $SiO_2$ | 50.59 | 50.89 | 58.00 | 57.45 | 55.16 |
| $Al_2O_3$ | 23.50 | 23.50 | 19.91 | 20.09 | 19.83 |
| $Fe_2O_3$+FeO | 9.25 | 8.78 | 4.5 | 6.0 | 6.4 |
| MgO | 4.14 | 4.03 | 2.80 | 4.55 | 3.11 |
| CaO | 0.69 | 1.07 | 4.86 | 1.47 | 4.87 |
| $Na_2O$ | 11.56 | 10.99 | 7.15 | 8.63 | 6.74 |
| $K_2O$ | 0.03 | 0.08 | 1.02 | 0.20 | 1.77 |
| $TiO_2$ | 0.12 | 0.27 | 0.85 | 0.83 | 0.70 |
| MnO | 0.12 | .0.10 | not det. | not det. | not det. |
| Total | 100.0 | 99.7 | 99.09 | 99.22 | 98.58 |

[1] Analysis by broad-beam electron microscope: semiquantitive only.
[2] Analysis by X-ray flourescence.

basaltic composition, but it is unlikely that basaltic pyroclastics are present because large amounts of pumice are more commonly produced during eruptions of siliceous, viscous magmas. The dacitic pyroclastics also contain albitic plagioclase, large amounts of pumice, and variable amounts of lithic clasts and glassy matrix, but are distinguished by the presence of more than 10 percent quartz (percentage of total minerals determined by point count). Some of these dacitic deposits contain as much as 40 percent quartz. Biotite and potassium feldspar are present in small quantities in a few of the deposits. A small number of rhyodacitic pyroclastic deposits containing more than 10 percent quartz and 10 percent potassium feldspar are scattered throughout the composite section.

Calculations of rock proportions in the composite section (pl. 3) indicate that the volcanics in the Complex consist of 35 percent andesitic-basaltic flows, 12 percent andesitic pyroclastics, 50 percent dacitic pyroclastics, and 3 percent rhyodacitic pyroclastics. The ratio of flows to pyroclastics is about 1:2. However, this ratio could be in error for the total late Paleozoic volcanic activity because a complete section of the upper Paleozoic volcanics has not been found. These data indicate the middle Pennsylvanian to early Permian volcanism was characterized by highly explosive dacitic eruptions. Eruptions of this type are characteristic of the large stratovolcanoes in the Tertiary and modern volcanic arcs of, for example, Japan, Kamchatka, and Indonesia. It seems likely that comparable stratovolcanoes dominated the late Paleozoic paleogeography in the map area.

## ENVIRONMENT OF DEPOSITION

The available evidence in the map area indicates that nearly all of the Tetelna Complex was deposited below sea level. Lenses of fossiliferous limestones and limey siltstones are common in these strata throughout the map area. Also, many of the graded sandstones and conglomerates contain fragments of marine fossils. The pyroclastic deposits are conformably interbedded with the fossiliferous deposits, and many of them also contain at least a small percentage of marine fossil debris. In addition, subaerial features such as plant debris, stream channels, and weathered zones were not found in any of the pyroclastic units.

One problematical pyroclastic deposit is unit Pbm, an exceptionally thick dacitic lapilli tuff. Although the lower part of this lapilli tuff conformably overlies the marine rocks of unit Pmc, the upper part is separated from the overlying Mankomen Group limestones by an erosional unconformity. It cannot be proved that the deposit is entirely subaqueous. However, none of the beds examined contain evidence of crossbedding, ripple marks, or other indications of tractive currents that would be expected if deposition had reached or continued above sea level. It seems likely that this unit also was deposited entirely below sea level.

Lava flows are present in unit ₱wf, and these are conformably interbedded with marine rocks. Although pillow structures are absent, these flows most likely are submarine. Unfortunately, unit ₱wg, which is composed entirely of flows, is completely separated from the rest of the Complex by a fault. Consequently, the environment in which these flows accumulated cannot be determined from the nature of associated sedimentary deposits. The flows in this unit are massive in places and brecciated in others; pillows appear to be absent. However, the lack of pillows does not necessarily eliminate a marine origin. In one thin section of these flows, nearly spherical fragments 0.5 to 1 cm across were observed. These resemble the spherical droplets sometimes formed when hot fluid lava is quenched by water.

There are also several indications that the environment of deposition in which most of the Complex accumulated was a moderately deep one, entirely below wave base. For example, current-produced features such as good sorting, large-scale cross bedding, oscillation ripple marks, and rip-ups are rare. Instead, the predominant sedimentary structures are graded beds, slump structures, and thin parallel bedding and laminations. These are structures typical of deposits that accumulate in quiet water below wave base. Furthermore, a minimum water depth of 150 to 700 feet is indicated for parts of the Complex by the thicknesses of several of the pyroclastic units. For example, map unit Pfc contains a coarse dacitic pyroclastic deposit that reaches a maximum thickness of nearly 300 feet (fig. 3, $WS_D$). This unit does not contain interbedded normal marine strata, and it is conformably overlain and underlain by slightly fossiliferous marine claystones and graded sandstones. The lack of interbedded marine deposits indicates that the pyroclastic unit was deposited rapidly during one major eruption. Thus a water depth of at least 300 feet must have existed at the time of the eruption to accomodate the 300 feet of pyroclastic material. Similar reasoning can be applied to other unbroken successions of pyroclastic deposits in units Pnc and Pbm, in which the deposits have respective thicknesses of 155 and 700 feet.

In a quiet-water environment below the limit of effective wave base, two major categories of sedimentary processes can be expected to have controlled sedimentation: settling from suspension, and subaqueous gravity flows. Strata in the Complex contain evidence of both of these processes, but the subaqueous-gravity phenomena were the most important and were largely responsible for the influx and deposition of sand-sized and coarser material. Gravity processes deposited at least parts of the pyroclastics and produced slumps and slides, debris flow deposits, and a variety of graded beds.

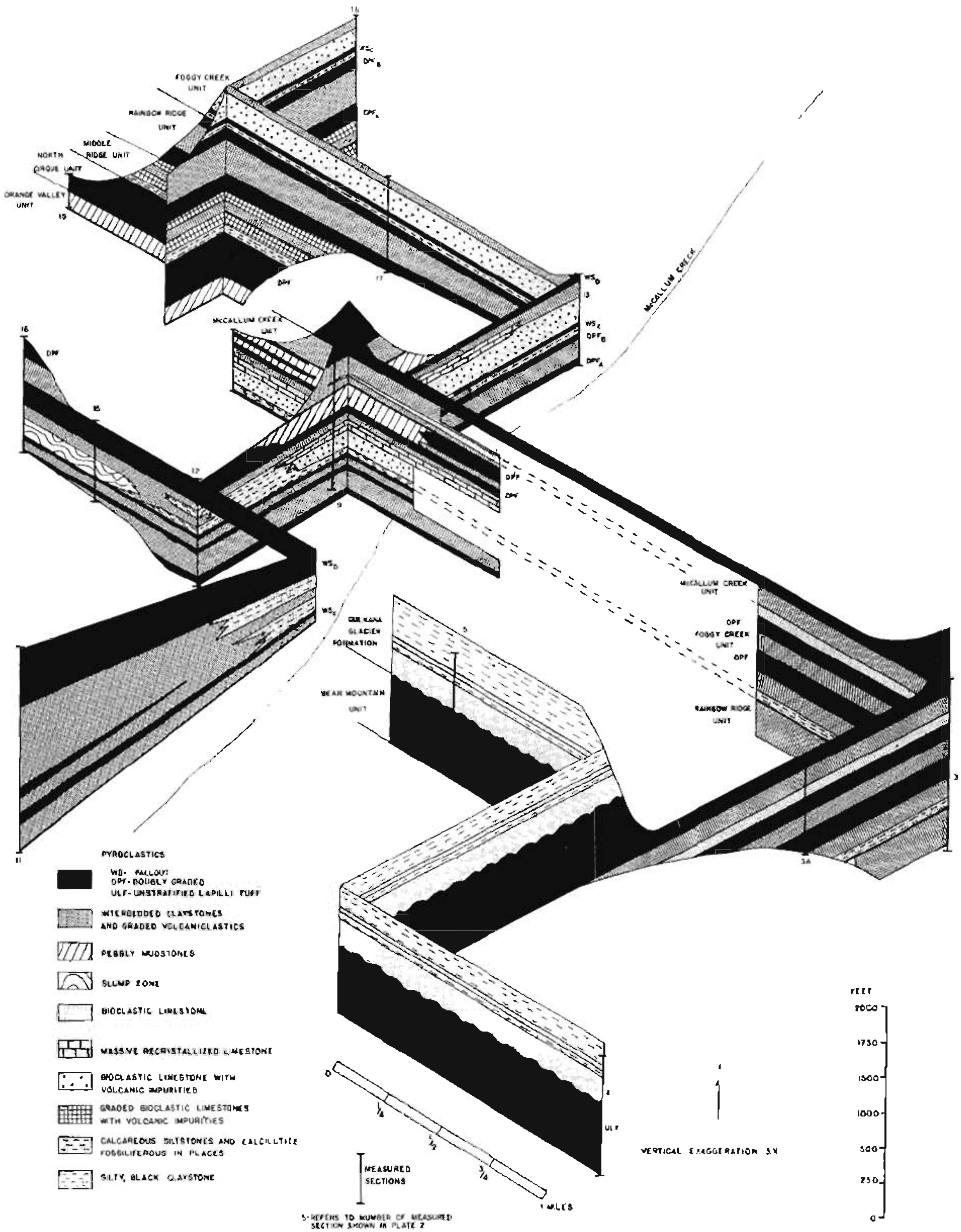

FIGURE 3.—Fence diagram showing lithofacies in the upper part of the Tetelna Complex.

## PYROCLASTIC DEPOSITS[1]

Over two-thirds of the Tetelna Complex is composed of pyroclastic rocks, and these are remarkably diverse in stratification, texture, and composition. Particular emphasis is given to these deposits because of their volumetric importance in the Complex, and because an understanding of their eruptive origin and their mode of deposition has an important bearing on paleogeographic interpretation and reconstruction of geologic history in the map area.

In the following discussion, the pyroclastic deposits are grouped into three categories on the basis of the inferred mode of deposition. The first category, pyroclastic fall deposits, are those believed to have been deposited directly by fallout through the water column. The second, mixed fall and flow deposits, consist of a lower part deposited from a marine pyroclastic flow and an upper part deposited by fallout. The third category, unstratified deposits, are those pyroclastics for which the depositional mechanism is uncertain. They may have been deposited by fallout or entirely from submarine pyroclastic flows. Most of the detailed work has been done on map units Pnc, Pr, Pfc, and Pbm (pl. 2); the discussion is primarily devoted to the pyroclastic rocks in these strata.

### PYROCLASTIC FALL DEPOSITS

#### LITHOLOGY AND PETROGRAPHY

A large number of the pyroclastic fall deposits in the Tetelna Complex consist of fine-grained tuffs. Many of these occur in the upper part of map unit Pnc (fig. 4), but they are also found sporadically throughout the Complex. On the outcrop surface these tuffs appear as distinctive greenish-white to medium-green beds, which range in thickness from 1 inch to slightly over 2 feet. Close examination usually reveals an indistinct stratification within the beds that is defined by slight differences in grain size, color, or graded bedding.

A few of the tuffs were examined in thin section. The identifiable ash-sized material is composed of broken albitic plagioclase crystals, quartz, potassium feldspar, and a small percentage of accessory lithic fragments. This crystal and lithic ash is embedded in a matrix that was probably fine glassy material but which has since recrystallized to an exceedingly fine (approximately 2- to 4-micron) light-green aggregate of quartz, feldspar, and chlorite flakes. Many of the samples contain layered concentrations of flattened chloritic platelets that have the porous or tubular texture indicative of pumice fragments. The grain size of the lithic and crystal material rarely exceeds that of coarse silt, and the tuffs typically are well sorted. The tuffs examined are probably dacitic to rhyodacitic in composition since they usually contain more than 10 percent quartz and potassium feldspar.

The good sorting and stratification in these deposits is evidence that the fine ash was spread in eruption clouds away from the eruptive vents and settled slowly through the water column to the se floor.

Two pyroclastic deposits in map unit Pfc deserve special emphasis because they are much thicker and coarser grained than the tuffs discussed above, and they give some indication of the location of the vents from which the pyroclastic material was erupted. These two deposits were used as stratigraphic markers for correlation, and for the purposes of this discussion the two units are named marker bed C and marker bed D. The stratigraphic position of these two deposits in the complex is shown in figure 3 ($WS_C$ and $WS_D$).

Marker beds C and D are characterized by a distinctive color and stratification. They range from light green to medium gray—a sharp contrast from the darker green of most of the other pyroclastics in the Complex. The stratification is typically defined by slight differences in grain size or color, and in many samples examined, by graded bedding (fig. 5). Individual layers in marker bed C are mostly fine- to coarse-grained tuffs that vary in thickness from less than 1 inch to about 6 inches. In marker bed D most of the beds are lapillistones, ranging in thickness from 4 inches to slightly over 1 foot. Both marker beds C and D have thinner and finer-grained beds in the upper and lower one-thirds of the deposits. Although this stratification is distinct from a distance, the contacts between the layers, if examined closely, are usually vague and difficult to locate (fig. 5). This is a bedding phenomenon also observed in many air-fall pyroclastics (Sigvaldason, 1968, p. 93-96; Wentworth, 1926).

A thin-section examination of selected samples from both deposits indicates that they are composed mainly of albitic plagioclase (50-70 percent) and quartz (30-40 percent); the original composition of these beds was probably dacitic. The plagioclase grains are generally angular broken fragments, and the quartz is typically embayed. Accessory lithic fragments of andesitic or dacitic composition occur but rarely in amounts greater than about 10 percent. Wispy, flattened pumice or scoriaceous fragments are randomly scattered throughout the individual layers.

The grain size of both deposits varies slightly ver-

[1]Pyroclastic terminology used in this report is after Fisher (1966, p. 292-296). *Ash* refers to unconsolidated particles ranging from clay and silt size (fine ash) to sand size (coarse ash). Consolidated rocks composed mostly of ash are called *tuff*. *Lapilli* refers to unconsolidated material ranging from 2 to 64 mm in diameter and is subdivided in the following manner: *very fine* lapilli - 2 to 4 mm; *fine* lapilli - 4 to 8 mm; *medium* lapilli - 8 to 16 mm; *coarse* lapilli - 16 to 32 mm; and *very coarse* lapilli - 32 to 64 mm. Consolidated lapilli is called *lapillistone*, and the term may be modified according to grain size by the prefixes given above. Poorly sorted pyroclastic rocks composed of about equal amounts of tuff and lapillistone are called *lapilli tuffs*. Pyroclastic deposits composed of fragments from 64 to 265 mm in diameter are called *fine pyroclastic breccias*; those composed of fragments mostly larger than 256 mm are *coarse* pyroclastic breccias.

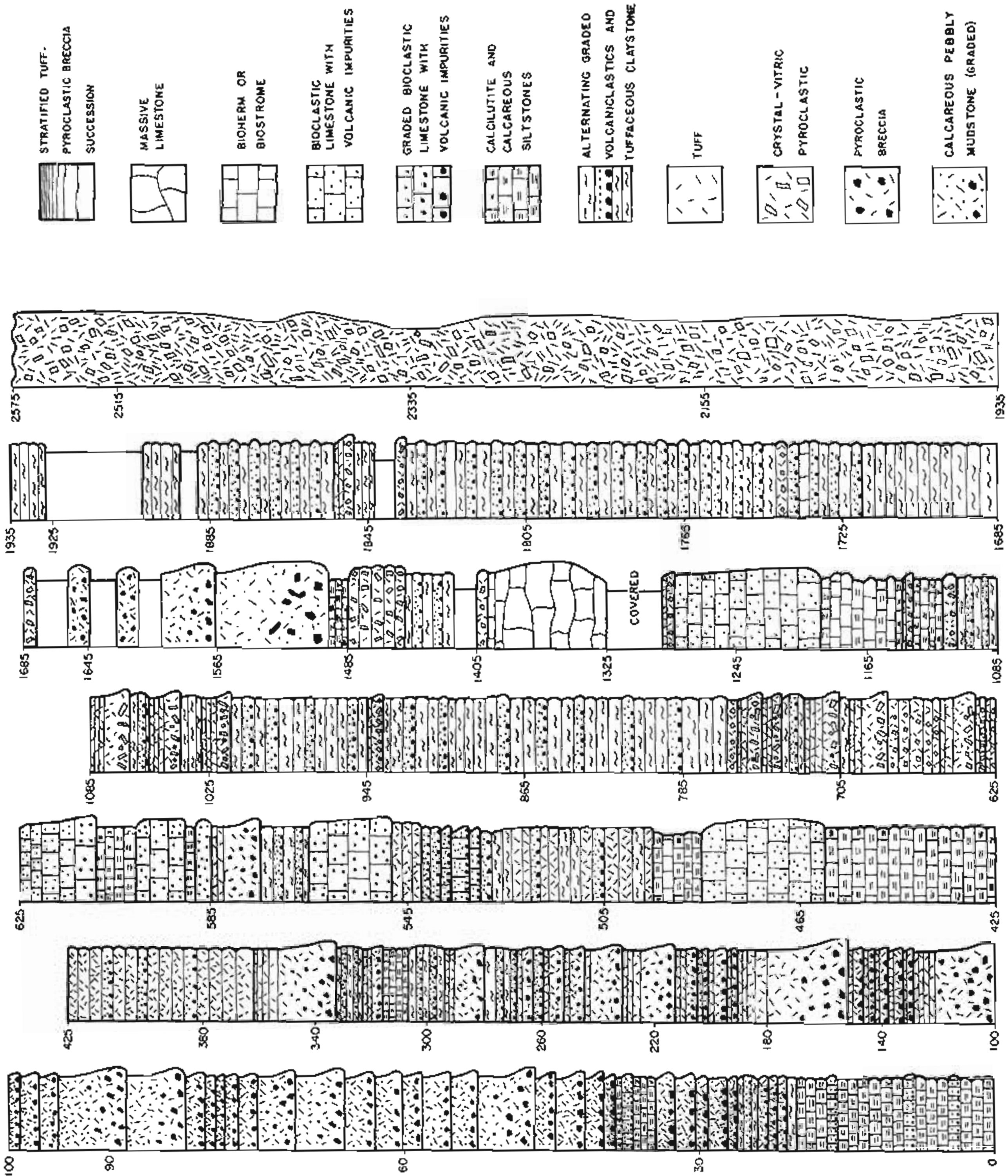


FIGURE 4.—Columnar sections through the upper part of the Tetelna Complex.


FIGURE 5.—Graded bedding in stratified pyroclastic fall deposit, marker bed C.

tically and significantly laterally (fig. 6). On the average, marker bed C is composed of fine to coarse ash, whereas marker bed D is composed of coarse ash to medium lapilli. Both units are moderately to well sorted.

The ash and lapilli are embedded in a fine-grained, recrystallized aggregate consisting mostly of quartz, feldspar(?), and a small amount of chlorite. Much of this aggregate has the interlocking granular texture of 'salt and pepper' extinction typical of completely recrystallized glass. In fact, several relict glass shards, now composed entirely of chlorite, could be distinguished within this recrystallized aggregate in a few samples.

### SEDIMENTATION OF MARKER BEDS C AND D

The potential for resedimentation of marine pyroclastic debris during explosive eruptions is quite high; however, it is unlikely that turbidity current sedimentation played an important role in the deposition of individual layers within marker beds C and D, despite the frequent occurrence of graded bedding in the deposits. The well-developed stratification, the moderately good to good sorting, and the gradational contacts between individual beds in both deposits are characteristics usually considered to be diagnostic of deposition directly from eruption clouds (Fiske, 1963, p. 397; Williams, 1926, p. 240-241; Ross and Smith, 1960, p. 18-22). In addition, many of the layers within the two pyroclastic deposits are lenticular and cannot be traced laterally for more than 100 to 200 feet. Lenticular stratification on this scale is not characteristic of turbidity current deposits. However, subaerial air-fall pyroclastic rocks have been described in deposits of the Katmai region of the Alaska Peninsula that are characterized by internal lenticular stratification comparable to that observed in the pyroclastics in marker beds C and D (Curtis, 1968, p. 167). Considered together, the characteristics of the pyroclastics strongly suggest that the individual layers in the two marker beds were deposited directly by fallout from eruption clouds rather than by turbidity currents. The lenticular stratification was probably produced by a combination of explosive pulses during the eruption and turbulence in the eruption cloud. The graded bedding in many of the individual layers can be attributed to the faster settling velocities of the larger-sized (heavier) fragments.

### SOURCE OF MARKER BEDS C AND D

The fallout origin of marker beds C and D is an important fact to establish because explosive eruptions are rarely capable of ejecting lithic lapilli—especially of medium size—more than a few miles from the vent (Rittmann, 1962, p. 74; Ross and Smith, 1960, p. 18-22). The significance of these two deposits, therefore, lies in the fact that their grain size requires the erupting vents to have been located probably no more than a few miles from the present exposures of the deposits. The probable direction to the vents is indicated in figure 6, which shows the thickness and grain-size variations of both deposits within the area. Although the data are scant, they indicate that marker bed C thins in an easterly direction. Also, the grain size in marker bed C decreases in an easterly direction. Too few data are available to determine the exact direction of thinning in marker bed D, but the two thicknesses known are consistent with an easterly or northeasterly thinning of marker bed C. It is inferred, therefore, from these data that the pyroclastic material in marker beds C and D was erupted from vents located only a few miles west or southwest of McCallum Creek. Unfortunately, Permian strata in the critical area to the southwest are mostly covered by Tertiary and Quarternary deposits, and the inferred location of the vents cannot be confirmed by more direct evidence.

## MIXED FALL AND FLOW PYROCLASTIC DEPOSITS

Most of the coarse-grained pyroclastics in the Complex belong to this category. These deposits are characterized by a distinctive stratification consisting of an ascending succession of graded beds that tend to become progressively finer grained (fig. 7). This type of layering was initially termed *double grading* by Fiske (1964,

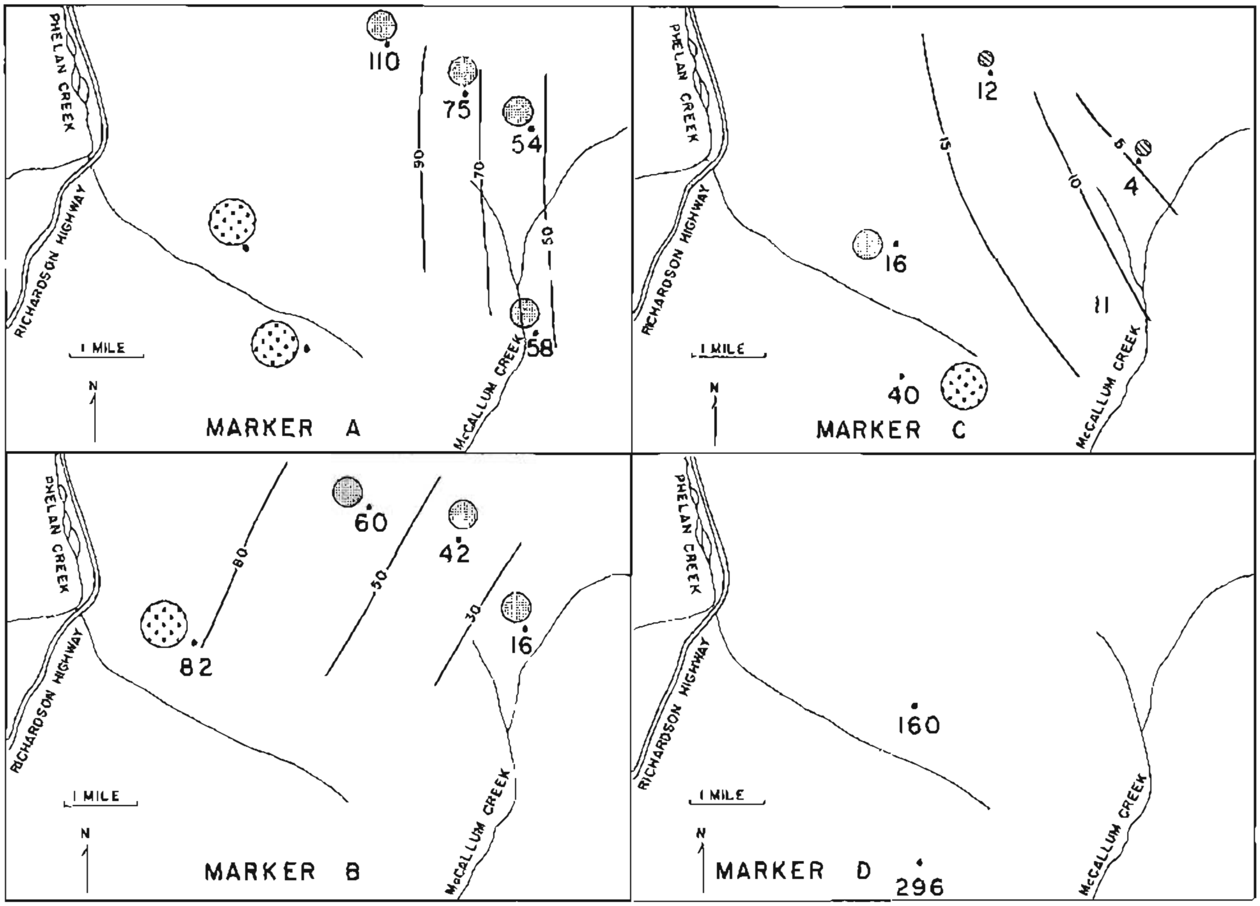


FIGURE 6.—Grain-size and thickness changes in four pyroclastic deposits in the Tetelna Complex.

p. 83-88) to describe a similar stratification in pyroclastic deposits of Japan.

Most of the doubly graded pyroclastics occur in the lower two-thirds of map unit Pnc (fig. 4) and at the top and bottom of the map unit Pn (fig. 4 and $DPF_A$ and $DPF_B$ in fig. 3). The deposits have a distinctive green to dark green color, and in the field they can be easily recognized from a distance. The thickness of the doubly graded deposits is variable, ranging from 5 to over 50 feet. Individual deposits are continuous laterally for about a mile, but thin markedly or pinch out within a distance of 3 to 4 miles.

The typical doubly graded pyroclastic unit can be divided into a lower zone, which is a massive, graded lapilli tuff, and an upper zone, which is composed of numerous, well-stratified graded tuffs and lapillistones (fig. 7). In some of the doubly graded intervals, the two zones are about equal in thickness, but typically the lower zone makes up only one-third to one-fourth of the deposit. In all of the exposures examined, the contact between the two zones is gradational; an indistinct stratification appears above the lapilli tuff, and becomes progressively more distinct higher in the upper zone of the deposit (fig. 7).

#### LITHOLOGY AND PETROGRAPHY OF THE LOWER ZONE

The lapilli tuffs in the lower zones are characterized by a chaotic mixture of lithic fragments, plagioclase crystals, pumice lapilli, and glassy ash. Quartz crystals are present in many of the deposits, especially in the Rainbow Ridge unit (Pr). The lithic fragments are angular and are extremely variable in size, ranging from fine ash to coarse lapilli. The fragments are basaltic-andesitic to dacitic, and exhibit a variety of textures, including porphyritic, trachytic, pilotaxitic, glassy, microvesicular, and scoriaceous. The plagioclase crystals are mostly broken fragments ranging in size from coarse ash to fine lapilli. They are almost entirely albitic and exhibit albite, Carlsbad-albite, and pericline twinning. Pumice lapilli are very abundant, commonly totalling as much as 40 percent of the pyroclastic debris (fig. 8). The pumice commonly occurs as irregular platelets and discs flattened parallel to bedding. The matrix in these deposits is a fine-grained aggregate of chlorite,

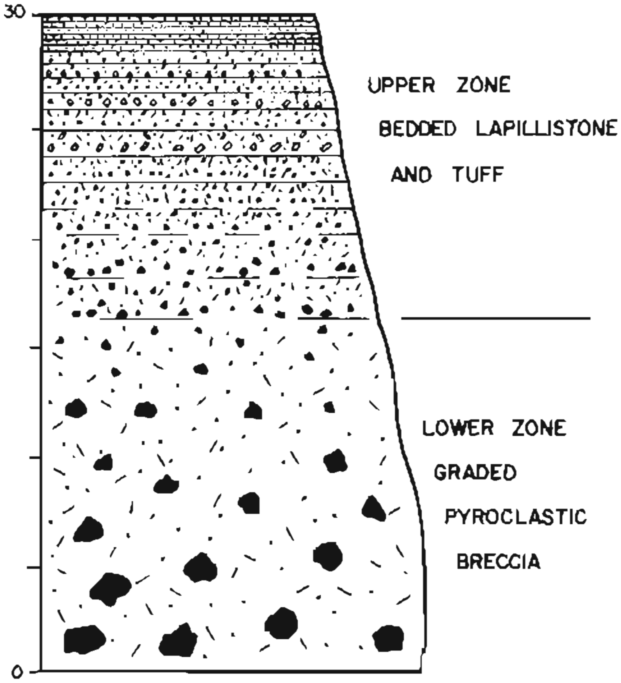


FIGURE 7.—Typical double grading in pyroclastic deposits of the Tetelna Complex.

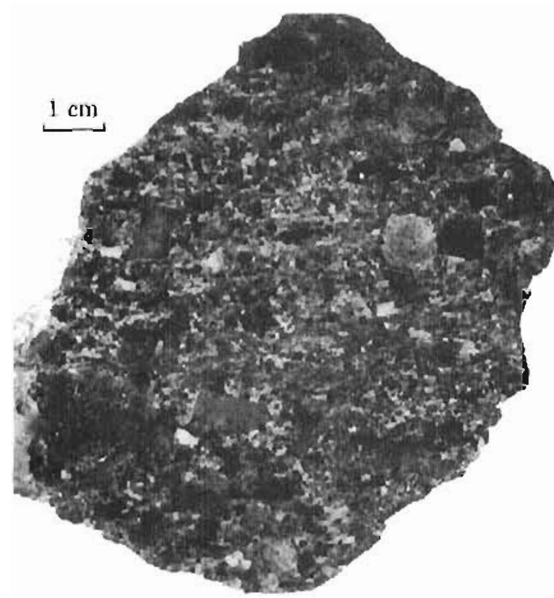


FIGURE 8.—Typical lapilli tuff from lower part of doubly graded pyroclastic deposits.

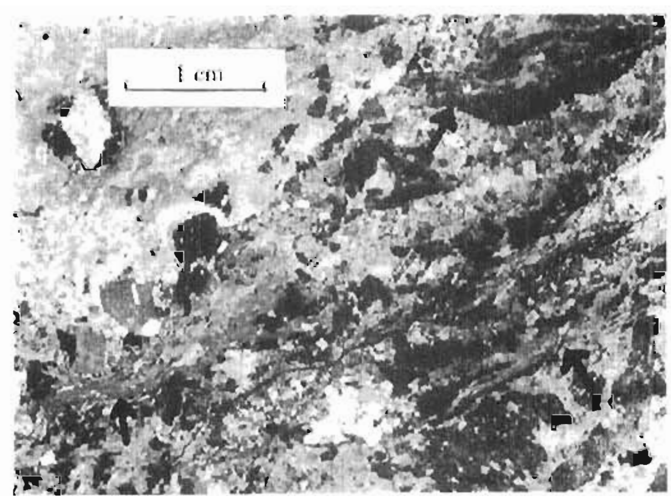


FIGURE 9.—Photomicrograph of lapilli tuff in lower part of a doubly graded pyroclastic deposit.

quartz, feldspar, and some leucoxene, and probably represents altered glassy dust and ash. Foreign fragments of corals, brachiopods, echinoids, and crinoids occur in nearly all of these lapilli tuffs, and claystone clasts similar to the bedded claystones in other parts of the formation were observed in several of the deposits.

The most significant features of these lapilli tuffs are the vertical size grading of fragments, the very poor sorting, and the lack of bedding. The grading is defined by an upward decrease in the size of lithic debris, typically from coarse lapilli at the base to ash at the top (fig. 7). In some of the lapilli tuffs, this vertical decrease in grain size is accompanied by a gradual increase in pumice and glassy fragments. The distinctive poor sorting can be seen in figures 8 and 9. This chaotic mixture of lapilli and ash occurs in all of the deposits examined, and it creates a markedly heterogeneous appearance that is strikingly apparent in the field. Bedding is absent, even in those lapilli tuffs that are over 20 feet thick. Although a crude discontinuous stratification is commonly present, it is defined by the alignment of elongated fragments parallel to the upper and lower contacts, and is in no way a phenomenon produced by successive depositional processes. Each massive lapilli tuff was undoubtedly deposited by a single sedimentation event.

### SEDIMENTATION OF THE LOWER ZONE

The lack of well-developed stratification and sorting in these lapilli tuffs suggests that they were not deposited by fallout from eruption clouds. Instead, these characteristics are more compatible with an origin by gravity-induced subaqueous flow. From studies in Washington and Japan, Fiske (1964, p. 83-84; 1963, p. 397-400) has recognized nonwelded subaqueous pyroclastic flow deposits that are composed of freshly erupted pyroclastic material dispersed along the sea floor by processes akin to turbidity currents. These deposits, like the lapilli tuffs in the map area, are characterized by a distinct lack of sorting and bedding. Fiske considered that these two features were diagnostic of an origin by pyroclastic flow rather than air-fall. Also, Ross and Smith (1960, p. 18-22) and Mauri (1961, p. 191-

199) have suggested that poor sorting and lack of well-developed stratification distinguish unwelded subaerial ash flows from most terrestrial air-fall tuffs.

Admittedly, thick deposits of poorly sorted, unstratified pyroclastics can be produced by fallout within the immediate vicinity of the active vent (Mauri, 1961, p. 199; Rittmann, 1962, p. 80), and these can be confused with unwelded ash flows (Ross and Smith, 1960, p. 21). However, the scattered fossil-shell debris and claystone clasts in the lapilli tuffs of the Complex are the kinds of material typically torn from the sea floor by turbidity currents or other subaqueous flowing masses, and the presence of this material in the lapilli tuffs is a further indication of an origin by flow. It is unlikely that the fossil debris could be accidental material incorporated during the eruption because some of the fossil fragments are parts of crinoid stems with as many as seven articulated columnals. The violence of a volcanic eruption probably would have fragmented delicate structures such as these.

An analysis of the flow mechanism by which the debris in these lapilli tuffs was dispersed is beyond the scope of this paper. However, the fact that each deposit is graded from bottom to top suggests that the flow was fluid and turbulent, and the pyroclastic debris probably was transported by turbidity currents of high density.

### LITHOLOGY AND PETROGRAPHY OF THE UPPER ZONE

The stratified upper zone of the doubly graded deposits contains several alternating light-gray and green beds (fig. 10). These beds range in thickness from 2 to 6 inches at the base of the zone, but tend to be less than 1 inch thick at the top. The grain size in the lower, thicker-bedded part of the zone typically is coarse ash or fine lapilli, whereas the grain size in the upper, thinner-bedded part is usually fine ash. This upward decrease in grain size and bedding thickness is not gradual and continuous, and there are many reversals in the trend; however, if the lowermost beds are compared with the upper beds, the changes are obvious. The top of this stratified zone commonly is a green, pumiceous, fine-grained tuff identical to the fine-grained fallout tuffs discussed in a previous section. Although the contacts between the light-gray and green beds appear sharp in hand specimen (fig. 10), thin sections across these contacts show that they are actually somewhat gradational.

As the contrast in colors suggests, the light-gray and green beds are markedly different in composition. The former beds are composed mainly of albitic plagioclase crystals, quartz, and a few lithic fragments embedded in a clear siliceous matrix that is probably a microcrystalline silica cement. In contrast, the green beds contain—in addition to quartz, albitic plagioclase, and lithic fragments—an exceptionally large volume of pumice and scoriaceous fragments, locally as much as 30 to

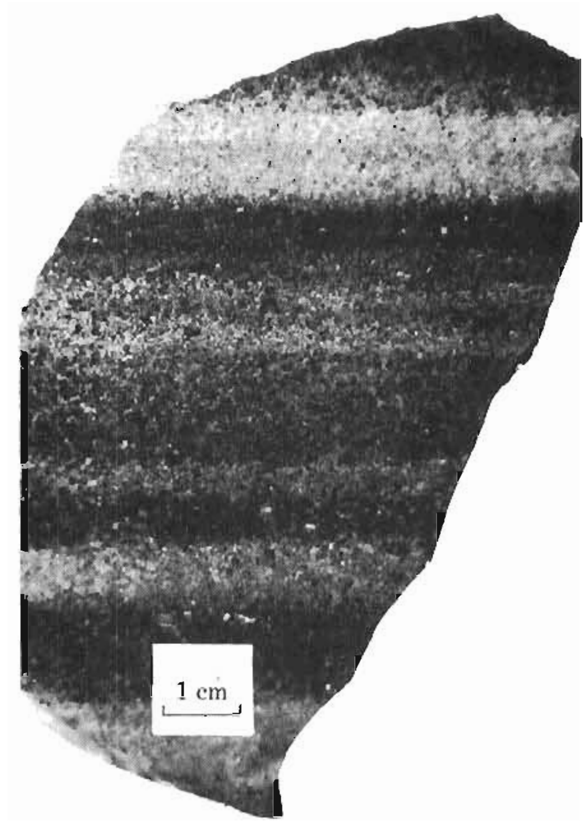


FIGURE 10.—Typical stratified pyroclastic deposit from the upper zone of a doubly graded pyroclastic deposit.

50 percent. The pumice and scoriaceous fragments have been replaced by chloritic minerals that give the beds their characteristic green color. The sorting of crystals and lithic fragments in the light-gray bands is moderate to good (estimated from thin sections). Sorting in the green bands cannot be estimated because of the large amount of highly altered pumice.

### SEDIMENTATION OF THE UPPER ZONE

In those deposits examined in detail, the well-developed stratification and moderate to good sorting in the upper zones strongly suggest a fallout origin for the tuffs and lapillistones. The combination of distinct stratification and difference in composition between the light-gray and green beds can be explained best as the result of a density segregation of the erupted debris while settling through water. During the eruption, each explosive pulse would have ejected a mixture of crystals, lithic fragments, pumice, and glassy ash into the water. As the mixture settled, the lighter, slower-settling pumice and scoriaceous material were separated from the denser, faster-settling crystal and lithic ejecta. Although complicated by many factors, each explosive pulse would tend to produce a couplet composed of crystals and lithic fragments at the base (light-gray beds), and pumice, glass fragments, and scoria at the top (green beds). The upward reduction of grain size and bedding thickness in the upper part of the zone probably would then be caused by a combination of waning volcanic activity and the slower settling of finer-grained ejecta. Marked separation of pyroclastic material by settling through water has been described by Fisher (1965, p. 351-353), Fiske (1964, p. 103), and Sigvaldason (1968, p. 4).

It could be argued that each light gray—green couplet was deposited by a small turbidity current carrying a slurry of pyroclastic debris away from the erupting vent, a process that was suggested by Fiske (1964, p. 93-96) to explain a somewhat similar doubly graded stratification in pyroclastic deposits in Japan. However, the graded beds are distinctly lenticular. As indicated in the discussion of marker beds C and D, this lenticularity is evidence of a fallout rather than a turbidity-current origin. Furthermore, the sorting in the light-gray part of the couplets appears to be much better than the sorting in samples of similar grain size from the lapilli tuff in the lower zone, interpreted as a product of turbidity-current deposition. This is further evidence of a fallout origin for the units of the upper zone because settling of debris through water should produce a better sorted deposit than the churning, turbulent flow of a turbidity current.

#### ERUPTIVE ORIGIN

Since the two zones in the doubly graded pyroclastics are gradational into each other, the subaqueous pyroclastic flows that deposited the lapilli tuffs must have been initiated by the eruptions that produced the upper zone tuffs and lapillistones. The initial explosion of the eruption must have ejected a large quantity of lithic fragments, crystals, pumice, and ash. The debris were immediately carried away from the vent by subaqueous flow. After the initial explosion, large quantities of crystals, pumice, and glassy ash were ejected in billowing eruption clouds. The pyroclastic debris in these clouds settled through the water and were deposited as stratified tuffs and lapillistones on top of the massive lapilli tuffs produced by the pyroclastic flows.

Similar eruptions have been noted in modern volcanic regions. In Indonesia, terrestrial pyroclastic deposits produced by a Pelean type of eruption consist of a lower chaotic tuff breccia laid down by a 'ladu,' or a pyroclastic block and ash flow, and an upper part consisting of air-fall lapilli and ashes that settled from eruption clouds (van Bemmelen, 1949, p. 192-194).

Although it cannot be determined if the deposits are welded, it is unlikely that welding could occur after the debris came into contact with sea water even if the eruptions took place below sea level. Fiske (1964, p. 84), for example, could find no evidence of welding in the subaqueous ash flows in Japan, even though the eruptions were inferred to have been the submarine equivalents of eruptions that produce welded tuffs on land.

#### SOURCE

The relatively coarse grain size in the tuffs and lapillistones of the upper zones indicates the proximity of the active vents, probably within a few miles of the area of investigation. The probable direction to these vents is shown in figure 6. This diagram summarizes thickness and grain-size variations in the two successions of doubly graded pyroclastics that occur at the top and bottom of map unit Pr (fig. 6). These are named marker bed A (lower succession) and marker bed B (upper succession). In the fence diagram (fig. 3), these two successions are shown as $DPF_A$ and $DPF_B$. Although the diagram in figure 6 shows a systematic thickening in a westerly direction, these data must be interpreted with caution because each doubly graded interval contains both deposits from subaqueous pyroclastic flows that moved down the local paleoslope and fallout deposits that were deposited as blankets on top of the flows independent of the topography. Conceivably, the direction from the erupting vents could be somewhat different than the down-dip direction of the local paleoslope. Consequently, the thickness variations would, in that case, reflect control by both factors. However, since two-thirds to three-fourths of the doubly graded intervals consist of fallout tuffs and lapillistones, it can be assumed that the direction of thickening indicates essentially the direction to the active vents. The source vents therefore must have been located a few miles to the west.

The grain-size measurements for deposits $DPF_A$ and $DPF_B$ shown in figure 6 are field estimates of the coarsest material in the lapilli tuffs of the lower zones. Since the decrease in grain size is a measure of the direction in which the subaqueous pyroclastic flows moved, the grain-size changes therefore indicate a paleoslope inclined down to the east; within the limits of error in the data, this is in agreement with the inferred direction to the active vents. It is concluded that the doubly graded pyroclastics were deposited on the eastward-dipping submarine flanks of a volcano(es) with active vents located a few miles to the west.

## UNSTRATIFIED DEPOSITS

#### LITHOLOGY AND PETROGRAPHY

This category is represented by only one pyroclastic deposit in the area, but the deposit is exceptionally thick and constitutes one of the map units in the Tetelna Complex—the Bear Mountain lapilli tuff (unit Pbm). The deposit is a medium- to light-green crystal-vitric lapilli tuff and, as it lacks potassium feldspar and contains up to 20 percent quartz, is probably dacitic.

The thickness of the deposit is between 600 and 700 feet; because the upper contact is an erosional unconformity, this is only a minimum estimate of the original thickness. The lower contact of the lapilli tuff is conformable, and the deposit always overlies the claystones at the top of map unit Pmc. No consistent variation in thickness or in grain size could be seen within the area of exposures examined, and the member almost certainly extends well beyond the map area.

The Bear Mountain lapilli tuff differs in several respects from the pyroclastics of the two previous types. It is at least three to four times thicker and is perhaps an order of magnitude greater in areal extent than any of the other pyroclastic deposits in the formation. Well-developed stratification was not seen in any of the exposures examined, and the deposit, seen from a distance, appears massive and completely homogeneous. Closer examination usually reveals the presence of a crude, very discontinuous banding, defined by the alignment of large, dark-green, elongated pumice or glassy fragments (fig. 11), but this is not a stratification produced by successive sedimentation events. Lenses with a high concentration of crystal ash and lapilli occur within the more vitric portions of the deposit, but these are not bounded by distinct bedding planes. If bedding originally was present in the deposit, it must have been poorly developed and was obliterated by metamorphism. None of the exposures examined exhibited graded bedding; the texture immediately above the lower contact is not significantly different from that observed throughout the deposit.

FIGURE 11.—Bear Mountain map unit.

The crystals in the lapilli tuff are quartz and angular, broken fragments of albitic plagioclase ranging in size from fine ash to fine lapilli. Pumice fragments, many of which are of the long tube variety, also are abundant. They range in size from less than a centimeter across to large, elongated bodies that in some exposures are nearly 1 meter long. As evident in thin section, the pumice tubes are filled with a distinctive, greenish chloritic material, making the original porous texture readily visible. A few lithic fragments, probably andesitic, were seen in the thin sections examined, but these are apparently rare in the deposit. The matrix is a brownish, microcrystalline aggregate of chloritic flakes and interlocking quartz-feldspar(?) granules, a texture and composition suggestive of an original glassy material. Only one or two faint traces of glass shards were found in thin section, but shards probably were more abundant originally and their outlines have been destroyed by subsequent metamorphism. The sorting of ash and lapilli is usually poor. The crystal fragments are scattered throughout the matrix without respect to size, and the fragments are rarely in mutual contact. The pumice fragments also are distributed in a random, unsorted manner. The amount of fine ash and dust appears to be very high, probably between 30 and 50 percent, although it should be pointed out that much of this matrix originally may have been coarser, ash-sized glassy fragments or shards.

### SEDIMENTATION

The poor sorting and lack of distinct bedding in the Bear Mountain lapilli tuff suggests either that it is composed of a thick succession of rapidly erupted tuffs deposited near a volcanic vent, or that it was deposited from a single or several closely spaced subaqueous pyroclastic flows. The absence of included mud clasts and fossils makes the choice between the two alternatives difficult. No evidence of scour was seen at the base of the deposit, but subaqueous pyroclastic flows do not always erode the substrate over which they move (Fiske, 1963, p. 400). The texture and bedding in air-fall tuffs deposited near vents typically change abruptly with increasing distance from vents, and the lateral homogeneity of the Bear Mountain lapilli tuff for a distance of over 8 miles probably is the best evidence that it is a product of flow rather than air fall.

### ERUPTIVE ORIGIN

The exposures of the lapilli tuff are too restricted to permit a thorough analysis of the eruption that produced the deposit, but the marked contrast between this lapilli tuff and the underlying pyroclastics points to a quite different eruptive mechanism than earlier ones. The absence of distinct stratification suggests that the entire lapilli tuff was rapidly deposited, and is evidence that, although the eruption may have consisted of several closely spaced explosive pulses, it was essentially a single eruptive event. The thickness of the deposit requires that a large volume of material was ejected in a relatively short period of time. Because the deposit contains an exceptionally large amount of pumice and glassy material and relatively few blocks of lava, the erupted material must have been of the frothy, viscous type with a very high gas content. These are features typical of the Krakatoan type of eruption as defined by Williams (1941, p. 253-265). During this type of eruption, an exceptionally large amount of viscous, frothy magma is erupted rapidly, and the resulting deposits may be hundreds of feet thick, unstratified (or vaguely stratified), pumice-rich lapilli tuffs.

Regardless of the eruptive mechanism, the event that produced the Bear Mountain lapilli tuff must have been one of the largest and most significant volcanic eruptions that occurred during the late Paleozoic in the map area.

## RESEDIMENTED NONPYROCLASTIC DEPOSITS

Resedimented nonpyroclastic deposits are common throughout the Tetelna Complex. These deposits include slumps and slides, pebbly mudstones, a variety of graded sandstones, and graded limestones.

### SLUMPS

Evidence of soft sediment slumping can be found on both a large and small scale in the strata of the Tetelna Complex. The large-scale phenomena occur in zones 10 to 70 feet thick, and are characterized by highly contorted faulted and folded beds, isolated masses of twisted beds, sand dikes, scattered areas of chaotic fossil rubble in a claystone matrix, and a general lack of continuous stratification. The smaller zones contain structures that are not as chaotic as in the larger, but which do exhibit a variety of small-scale faults, folds, pull-aparts, and other soft-sediment deformations. These smaller features are commonly confined to beds not more than 3 to 5 feet thick. Soft-sediment slumps occur in every member of the Complex and are so numerous that practically every outcrop contains some evidence of this phenomenon. It is not difficult to conclude that the strata were deposited on a submarine slope that must have been relatively steep.

The orientation of nine folds in the larger slump zones were measured in an attempt to confirm the orientation of the paleoslope suggested by grain size and thickness changes in the subaqueous pyroclastic flow deposits. The strike of these folds was found to be in a northwest direction, which suggests that the strike of the paleoslope was also northwest (fig. 12). Significantly, the northwest strike of the paleoslope indicated by these slump structures is compatible with the postulated northerly strike of the paleoslope inferred from grain-size and thickness variations in the subaqueous pyroclastic flow deposits (fig. 6).

### DEBRIS FLOW DEPOSITS

#### LITHOLOGY AND PETROGRAPHY

Most of the debris flow deposits in the Complex occur in the Orange Valley unit (map unit Pov, fig. 4). These deposits are green to greenish white on fresh surfaces and are usually a distinctive, dull grayish green on weathered surfaces. The individual beds range in thickness from a few inches to slightly over 10 feet, and most of the beds can be traced for over 100 yards without noticeable variation in the thickness. This succession is persistent throughout the area west of Gulkana Glacier, and although exposures are generally poor except in the western part of the area, the overall grain size and thickness of the deposits appear to decrease in a northeasterly direction.

The most striking characteristic of the debris flows in the Orange Valley unit is their very poor sorting, a feature best illustrated by the presence of large, angular fragments from 5 to 20 cm across that are dispersed in a mixture of sand, silt, and mud-sized material (fig. 13). Many of the fragments are disk-shaped or flat, and they tend to lie with their flat surfaces parallel to the bedding, defining in some places a crude stratification (fig. 13). The base of some of the deposits truncates the upper parts of the underlying units, probably an indication of scour during deposition. Although the grain-size distribution is chaotic throughout the lower and middle parts of each bed, the clastic fragments are nearly always graded in the upper 2 to 3 feet of the thicker beds (shown diagrammatically in fig. 4). At the top of these graded intervals, there is usually a zone of parallel laminations 3 to 4 inches thick.

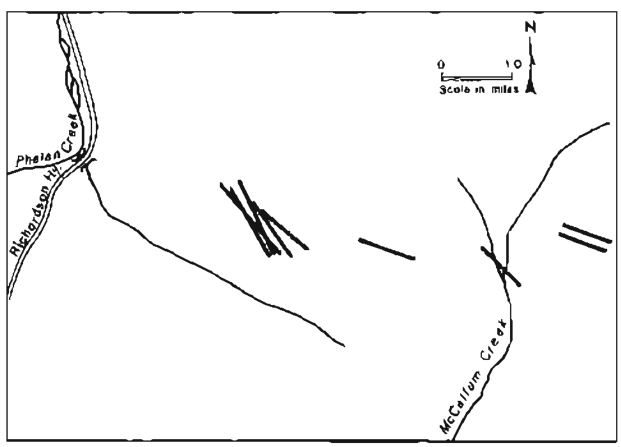


FIGURE 12.—Orientation of slump fold axes in the Tetelna Complex.

FIGURE 13.—Orange Valley map unit.

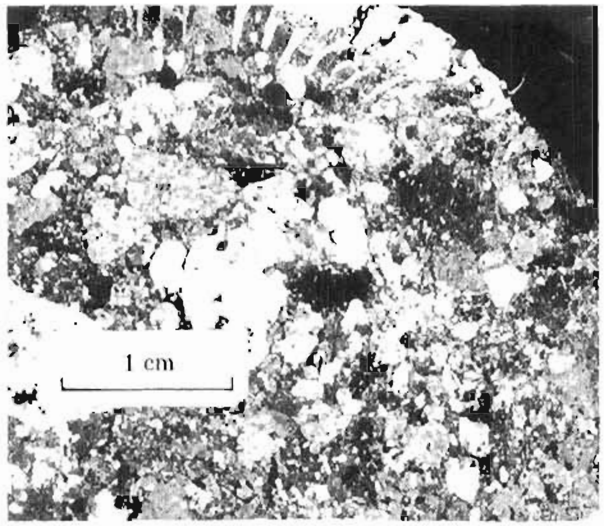


FIGURE 14.—Photomicrograph of sample from the Orange Valley map unit.

The composition of grains (material coarser than fine silt) in the Orange Valley strata consists of a mixture of fossil debris, volcanic rock fragments, plagioclase, and quartz (fig. 14). The fossil debris consists mostly of crinoid stems and pieces of brachiopods, echinoids, and broken coral calyxes. No fragments of lithified carbonate were found. The recognizable rock fragments probably are andesitic to dacitic, although the extensive alteration and decalcification make exact determination difficult. The textures of the rock fragments, although partly destroyed by the alteration, appear to be mostly trachytic, pilotaxitic, scoriaceous, pumiceous, glassy, and pyroclastic. Most of the rock fragments are angular and subangular, but many of the larger ones show some evidence of rounding. Significantly, a few of the sand-sized grains are rounded to subrounded (fig. 14). Detrital plagioclase grains are mostly albitic with Carlsbad, Carlsbad-albite, and some pericline twinning. Zoned plagioclase crystals are rare, and staining of several hand specimens failed to indicate the presence of potassium feldspar. These detrital plagioclase grains are identical in composition and twinning to the plagioclase phenocrysts in the rock fragments. The matrix (clay and fine silt size) is mostly secondary material composed of microcrystalline quartz, fine chloritic flakes, and a small amount of finely disseminated leucoxene. The original composition of this matrix could not be determined.

A smaller, more restricted interval of debris flow deposits occurs in the upper part of the Foggy Creek unit (map unit Pfc). This unit is a lenticular body found only in those outcrops of the Foggy Creek unit in measured section 9 (pl. 2). This interval grades laterally to the west and east into pyroclastic deposits (fig. 3).

The debris flows in the Foggy Creek strata have the same mixture of fossil and volcanic debris found in the Orange Valley deposits, and the lower part of each bed contains pebbles and cobbles of volcanic material suspended in a finer grained matrix. The Foggy Creek deposits differ from those in the Orange Valley unit in two respects. The Foggy Creek deposits contain a sericitic instead of a chloritic matrix, which gives them a grayish-brown rather than green color. Also, the individual deposits in the Foggy Creek unit are much thicker, varying from 30 to 50 feet in thickness. The upper 10 to 30 feet of each deposit is always graded, and the grain size ranges from coarse pebbles in the lower parts of the graded interval to fine sand at the top. As in the Orange Valley strata, the top of these graded intervals is thin-bedded or laminated, but this stratified zone is usually 1 to 2 feet thick rather than a few inches. In fact, if it were not for the ungraded, typical pebbly mudstone texture in the lower parts of these deposits, the beds would more closely resemble thick, coarse-grained turbidites. These deposits are quite similar in texture and stratification to the complexly stratified 'fluxoturbidites' reported to occur in flysch successions in those parts of flysch basins that are presumably near the source (Dzulynski, et al., 1959, p. 1095).

## SEDIMENTATION

Debris flow deposits such as those in the Orange Valley and Foggy Creek units have been shown to be the product of subaqueous mass flow initiated by sediment failure on a submarine slope. When the liquid limit is exceeded in the metastable, water-rich sediments, the masses move swiftly downslope by viscous, turbulent flow, a process that is responsible for the poor sorting and general absence of stratification (Dott, 1963, p. 113-114; Crowell, 1957, p. 1003-1005). During the flow of the deposits in the Orange Valley and Foggy Creek units, sea water apparently mixed with the upper part of the moving debris, reducing viscosity sufficiently to allow true turbidity flow to develop in the surface layers of the mass; this resulted in the graded and laminated upper parts of the deposits.

A number of factors may have caused the sediment failure that initiated the movement of material downslope. Rapid deposition, entrapment of large quantities of pore water during sedimentation, liquefaction, and sudden shocks may have been important contributors to the phenomenon (Crowell, 1957, p. 1004; Dott, 1963, p. 114-116). However, in a volcanically active region, sediment failure would be especially apt to occur during a volcanic eruption as a result of both rapid deposition of pyroclastic material and earthquake shocks accompanying the eruptions. It is important in this respect to recall that the Foggy Creek pebbly mudstone could be traced laterally into pyroclastic deposits, demonstrating their synchroneity. Furthermore, this mudstone interval also contains scattered lenses of dacitic tuffs (fig. 3). Both facts suggest that the flow of debris leading to the deposition of the Foggy Creek pebbly mudstones was initiated during volcanic eruptions, probably by rapid sedimentation or earthquakes, or both. Although the pebbly mudstones in the Orange Valley unit could not be traced into contemporaneous pyroclastic deposits, many of these deposits are overlain by 1 to 2 inches of fine tuff. It is likely that sediment failure occurring during volcanic eruptions was also a major factor in the production of the Orange Valley deposits.

## GRADED SANDSTONE DEPOSITS

### LITHOLOGY AND PETROGRAPHY

Graded sandstone deposits are distributed throughout the Complex, but they are particularly notable in the McCallum Creek unit, where they compose nearly 20 percent of the stratigraphic thickness (fig. 4). These deposits are gray, gray brown, or gray green, and range in thickness from less than 1 inch to over 3 feet. Individual beds typically are interstratified with laminated or massive silty claystones a few inches to several feet in thickness, a stratification pattern similar to the sand-shale interbeds characteristic of turbidite or flysch successions in other parts of the world. The graded sediments differ from many turbidites, however, in that the deposits have no internal current features such as crossbedding, convoluted bedding, parallel lamination, or ripple-drift lamination. Sole marks, if present, could not be seen because the lower surface of the graded units is usually firmly cemented by silicification to the underlying claystones.

The textural properties of the graded deposits (fig. 15) are those typical of many immature, graded graywacke sandstones. Within any single graded unit, the grain size may range from medium pebbles at the base to fine sand at the top; the coarser sizes tend to occur in beds thicker than 1 to 1.5 feet. A few notable exceptions were observed in which the grain size ranges

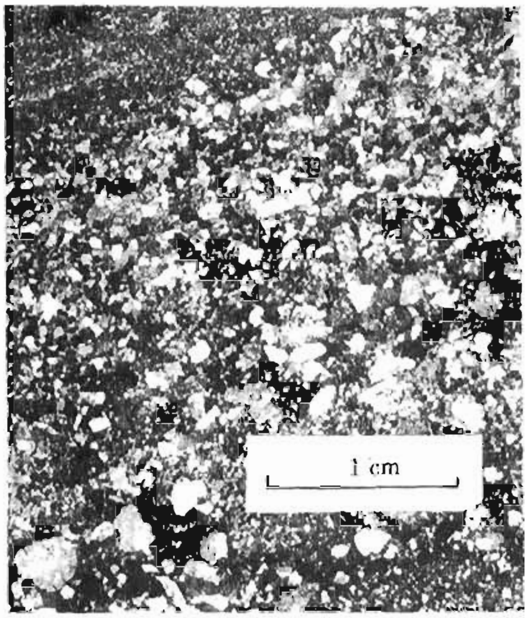


FIGURE 15.—Photomicrograph of a graded bed from the Tetelna Complex.

from medium pebbles to medium sand in beds less than 3 inches thick. Most of the detritus is angular to subangular, although some samples had a significant number of rounded to subrounded rock fragments. The sorting of grains in any part of the graded bed is poor, but not to the extent that the larger fragments appear to be suspended in a finer grained material as in the pebbly mudstones. The matrix content varies from as little as 1 to 2 percent to as much as 20 percent by volume (values estimated from thin section). Some of the deposits, especially those that have small amounts of matrix, are cemented by what is probably secondary chlorite occurring in the form of elongate sheaths growing in a cockscomb pattern between the detrital fragments.

The composition of grains is generally similar to the composition of the volcanically derived detritus in the pebbly mudstones. Andesitic(?) rock fragments, plagioclase, and quartz are present in variable proportions, although rock fragments with pyroclastic, pilotaxitic, trachytic, and glassy textures tend to predominate. Rock fragments with scoriaceous and pumiceous textures are present in some of the sandstones, but they are rarely important components. In some samples, the more porous of these vesicular fragments are compressed around the denser detrital grains, producing a 'pseudowelded' texture, which is probably the result of a combination of compaction and alteration. The quartz and plagioclase in these deposits are similar in size, shape, and composition to those in the pebbly mudstones. As is true of the pebbly mudstones, the detrital quartz and plagioclase are identical to the quartz and plagioclase in the rock fragments, indicating that these components also are probably derived from volcanic rocks. The matrix is a dark, microcrystalline aggregate of chlorite and leucoxene with minor amounts of quartz and feldspar; the matrix is probably an alteration product of mostly clay minerals because it contains no relict fragments of pumice or glass shards and because it is much darker than the matrix of the pyroclastic rocks (probably due to the presence of very fine carbonaceous material).

### SEDIMENTATION

The depositional origin of the graded sandstones is difficult to determine. The presence of graded bedding suggests a turbidity-current origin; however, such a hypothesis must be considered carefully because graded bedding in deposits composed of angular, volcanic rock fragments could have been formed simply by gravitational settling of the coarse debris produced after a volcanic eruption of predominantly lithic material. In other words, the graded sandstones could be lithic pyroclastics deposited directly from eruption clouds. The problem is particularly evident in that these deposits in the Complex lack the displaced fauna and internal stratification characteristic of turbidites in other parts of the world.

On the other hand, the graded sandstones differ in many respects from pyroclastics. The deposits contain very little glassy matrix or pumice and scoriaceous fragments, and pumice or ash rarely occurs at the top of the graded beds. The sandstones occur as single unstratified beds separated by thick intervals of claystone, and if they were produced by settling following volcanic eruptions, the eruptions would have to have been single explosions separated by long time intervals. However, an eruption typically consists of several explosive pulses, and these pulses are partly the cause of distinct layering or stratification in deposits formed directly from eruption clouds.

More compelling evidence can be cited, however, to show that the volcaniclastics are most probably the product of resedimentation processes. A few of the deposits contain scattered, small mudchips (1 to 2 cm across) whose texture and composition resemble those of the interbedded silty claystones. Mudchips such as these are common in turbidites and are thought to be fragments of cohesive mud ripped from the sea floor, presumably during passage of the turbidity current. In addition, the presence of rounded to subrounded rock fragments in several of the graded beds is evidence that some of the detrital material is not freshly erupted debris but instead underwent a period of abrasion before final deposition.

The combined presence of mudchips, rounded grains, and graded bedding in these graded beds is considered to be strong evidence that these beds were deposited from turbidity currents. The lack of internal stratification is not unusual in turbidites, and this may be due to deposition near the source of the turbidity current, an explanation offered by Walker (1967, p. 1018-1020).

## GRADED LIMESTONE

### LITHOLOGY AND PETROLOGY

Many of the carbonate units in the Tetelna Complex exhibit graded bedding. Although these rocks are classified as limestones, they are discussed under this heading because they were deposited by resedimentation processes. The graded limestone beds occur almost entirely in the Middle Ridge unit (Pmr), but a few beds are also found in the lower part of the Orange Valley unit (fig. 4). Although figure 4 shows only three graded limestone beds in the Middle Ridge strata, this small number is exceptional; as many as 20 to 30 are present in sections measured in other parts of the area. The color of these deposits varies from gray green (relatively large amount of volcanic impurities) to gray or grayish white (mostly carbonate debris). Individual beds typically are a few inches thick in the Orange Valley unit and 1 to 10 feet thick in the Middle Ridge unit. Unlike the graded volcaniclastics, these graded limestones are interbedded with a variety of lithologies, including calcareous siltstones, graded volcaniclastics, and pyroclastics. The individual beds also contain, in their upper parts, internal stratification in the form of horizontal laminations and small-scale planar cross bedding. As is true of other graded units in the formation, the lower surfaces of the graded limestones are too poorly exposed to reveal sole marks, if any.

The texture of these graded limestones is similar in many respects to the texture of the graded sandstones. The grain size of the carbonate and volcanic fragments in the thicker beds usually ranges from coarse pebbles (calcirudite) at the base to fine sand (calcarenite) at the top. Typically, the average grain size is inversely related to the thickness. The coarsest grains are usually the volcanic rock fragment impurities, but a few large fossil fragments, 2 to 3 cm across, occur in the lower parts of some of the thicker beds. Most of the volcanically derived grains are angular to subangular, but a few are rounded to subrounded. The margins of the detrital carbonate are so badly corroded that rounded surfaces, if originally present, have been destroyed. The individual graded beds are poorly sorted throughout, and the matrix content ranges from less than 5 percent in some beds to as much as 15 percent in others.

The composition of the graded limestones is somewhat similar to the carbonate-volcanic mixture characteristic of the pebbly mudstones in the Orange Valley strata, except that the percentage of volcanic detritus is much lower in the graded limestones. Most of the volcanic detritus is composed of andesitic(?) rock fragments with trachytic, pilotaxitic, glassy, and pyroclastic textures, and the detritus also includes volcanically derived quartz and albitic plagioclase. However, in some of the beds, a surprisingly large number of the volcanic impurities are dark-green pumice fragments that are usually much larger (4 to 5 cm across) than the other detrital components. All of these pumice fragments only to emphasize the contrast between it and the underlying strata of the Tetelna Complex.

## WEST OF GULKANA GLACIER

West of Gulkana Glacier, the lower 200 feet of the Mankomen Group (unit $Pl_1$, pl. 2) consist of an almost cyclic arrangement of thin- to medium-bedded units of calcilutite, calcarenite, and fine calcirudite (fig. 16). The calcarenite and calcirudite are composed of moderately to well-sorted bioclastic detritus embedded either in a micritic matrix or in sparry cement. The bioclastic material is a heterogeneous mixture of coral, bryozoan, brachiopod, echinoid, crinoid, fusulinid, and algal(?) fragments. Planar cross bedding 6 inches to 1 foot was observed in a few exposures.

The uppermost 10 to 20 feet of this 200-foot limestone interval is fine-grained and silty, and grades upward into black silty claystone. The black claystone, except for one 10-foot bed of calcirudite, characterizes the remaining part of the Mankomen Group exposed west of Gulkana Glacier (unit Pma, pl. 2).

The abundance of well-bedded, moderately to well-sorted, and occasionally cross-bedded bioclastic limestones indicates that, in contrast to strata in the Tetelna Complex, the lower part of the Mankomen Group was deposited in a relatively shallow marine environment above wave base. This shallow sea floor must have been heavily populated by benthonic organisms, which contributed abundant carbonate detritus to the local site of deposition. The gradual change from limestone to black shale at the top of the 200-foot limestone interval probably indicates a slow subsidence of the shallow, agitated environment to a depth at which bottom agitation was considerably reduced and conditions were no longer favorable for the development of organic communities. These conditions persisted long enough for at least 300 feet of black silty shale to accumulate.

## EAST OF GULKANA GLACIER

East of Gulkana Glacier, the Group consists of four facies: a bryozoan biostrome facies of which about 500 feet are exposed (lower part of $Pml_2$); a bioclastic limestone facies 300 feet thick (upper part of unit $Pml_2$); a facies composed of black argillite (Pma); and a facies composed of interbedded bioclastic limestone, black shale, and silty fossiliferous limestone (unit Pmla), of which approximately 600 feet are exposed. Sections measured through unit $Pml_2$ (section 2) and Pmla (section 2A) are described in appendix I.

Faulting, poor exposures, and severe recrystallization prevented more than a superficial examination of these facies east of Gulkana Glacier. The bioclastic limestones are thin- to medium-bedded calcarentite and calcirudite with moderate to good sorting and some cross bedding. The bioclastic debris appears to be mostly echinoderm and bryozoan fragments. Like the lower part of the Group west of Gulkana Glacier, these bioclastic limestones were apparently deposited above the local wave

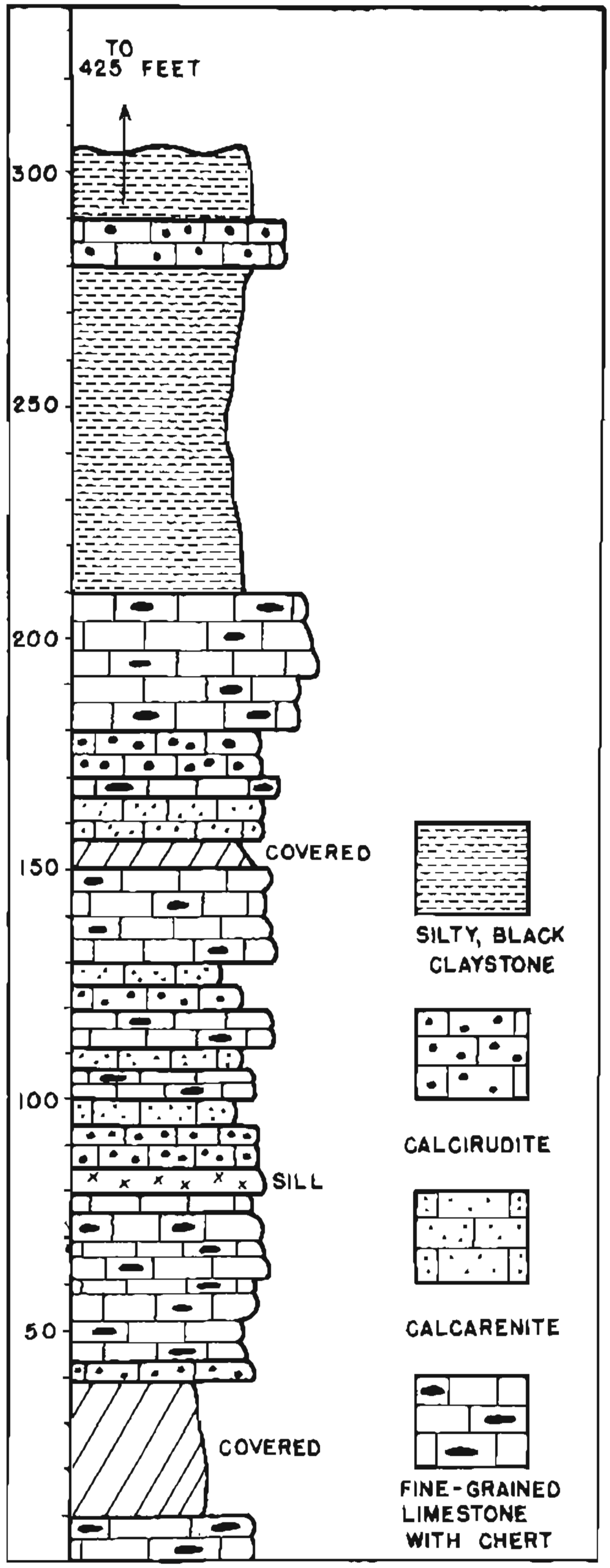


FIGURE 16.—Columnar section showing vertical lithologic changes in the lower part of the Mankomen Group (map unit $Pml_1$).

base next to large organic communities. The bryozoan biostromes are commonly less than 1 foot thick, and are composed almost entirely of fenestrate and ramose bryozoans. The bryozoans are mostly broken and scattered, but a few of them appear to have formed a framework structure. The matrix in these biostromes is mostly calcilutite. The silty fossiliferous limestones contain mostly spiriferid brachiopods and bryozoans embedded in a calcareous matrix with silt-sized quartz and feldspar impurities.

Some of the bioclastic limestone beds near The Hoodoos contain lenses of well-rounded and well-sorted calcareous terrigenous sandstone and fine pebbly conglomerate. In thin section, the terrigenous grains were found to contain a surprisingly large number of quartzite and quartz-sericite schist fragments, together with abundant chert fragments and a few volcanic rock fragments. This occurrence marks the only important concentration of metamorphic rock fragments within the upper Paleozoic strata in the map area.

## PALEOGEOGRAPHIC SYNTHESIS AND GEOLOGIC HISTORY

### MIDDLE PENNSYLVANIAN TO EARLY WOLFCAMPIAN

#### ACTIVE VOLCANIC SOURCE AND PALEOSLOPE

Evidence of the active volcanic source and the orientation of the paleoslope has already been discussed in the section on pyroclastics; therefore only a brief summary of the conclusions is given here. During middle Pennsylvanian to early Wolfcampian time, an active volcanic source area (probably a group of marine stratovolcanoes) continually supplied pyroclastic and nonpyroclastic debris into a moderately deep marine environment. In the lower Permian strata, the variation in thickness and in grain size of pyroclastics deposited from eruption clouds indicates that the volcanoes lay only a few miles to the west of the area of investigation. Grain-size changes in pyroclastics deposited from subaqueous pyroclastic flows indicate that the active vents were linked to the basin by a paleoslope inclined down to the east.

#### WATER DEPTH IN THE SOURCE AREA

The numerous well-rounded sand-sized rock fragments in some of the resedimented deposits must have been abraded by current action prior to transport downslope into the deeper parts of the environment. Admittedly, some potential for rounding exists in the process of flow of the debris downslope, particularly in the coarse material, but it is highly unlikely that grains of sand size could be rounded during flow in the short distance between the volcanic source and the local basin of deposition. Therefore, the rounded grains, especially those of sand size, are evidence that the active vents in the source area were located in a relatively shallow, wave-agitated environment.

That the active volcanoes rose above sea level as volcanic islands cannot be determined from the available data. However, since the vents apparently were located in relatively shallow water, it seems likely that from time to time explosive volcanism could have raised the vents above the surface of the sea.

#### DEPOSITIONAL SETTING

The environment of deposition was probably located on the outer flanks of the active volcanoes during early Wolfcampian time (fig. 17). The absence of current structures in the strata indicates a quiet-water environment, and this, together with the thicknesses of the pyroclastic deposits, is evidence that the water depth corresponded to the middle or outer part of the neritic zone. Small coral, brachiopod, and bryozoan bioherms and biostromes developed on the sea floor. Their growth probably was restricted in large part by the rapid deposition of pyroclastic debris following eruptions, and by frequent subaqueous mudflows and turbidity currents moving downslope across the basin.

The thickness of the volcanogenic strata, together with the absence of unconformities and the lack of evidence of shoaling conditions in the formation, indicate that subsidence must have kept pace with sedimentation.

#### SUBSEA FANS

An examination of figure 3 shows that as strata in the upper part of the Complex are traced eastward, some of the pyroclastic and sedimentary beds disappear, and an entirely new succession of pyroclastic and sedimentary deposits is found in the area immediately west of Gulkana Glacier. Although strata in the latter part of the area are not exposed enough to permit detailed study, the thickness of one pyroclastic deposit was found to increase to the south from 65 feet in measured section 3 (fig. 3) to 95 feet in measured section 3A (pl. 2, fig. 3). This evidence of southward thickening and the significant change in stratigraphy to the east may indicate that another active vent (or group of vents) was located to the south or southeast of the area of investigation. The pyroclastics in this area immediately west of Gulkana Glacier are mostly of the doubly graded type. The upper parts of the doubly graded intervals are composed of coarse ash and fine lapillistones, indicating that the vents that erupted the pyroclastics in this part of the area were only a few miles distant.

It is suggested from these stratigraphic relationships that at least the upper part of the Complex was deposited as a large wedge consisting of at least two subsea fans that formed on the flanks of the active volcanoes. One of these fans, which constitutes most of the upper part of the Complex, radiated eastward, away from the vents postulated to the west. The other radiated northward, away from the vents that probably occur as flattened disk-shaped bodies, with their short axis more or less perpendicular to bedding. The recognizable detrital carbonate is entirely fossil debris---crinoid stems, echinoid plates, pieces of brachiopods and corals, bryozoan fragments, and a few fusulinids. The matrix consists of fine detrital carbonate and an aggregate of microcrystalline quartz and chlorite.

### SEDIMENTATION

The presence of graded bedding, together with poor sorting and some internal stratification in these bioclastic limestones, almost certainly indicates a turbidity-current origin for these deposits. The abundance of fossil debris further suggests that the turbulent flows originated near organic communities---perhaps reefs or banks---located upslope in shallower water in places where conditions were favorable for the development of relatively large carbonate environments. Probably, occasional slumping of the carbonate debris in these environments led to the formation of turbidity currents that carried the carbonate debris and volcanic impurities---perhaps present as foreign material in the organic community---downslope to the deeper parts of the basin. Graded limestones or carbonate turbidites are not unusual; graded carbonate deposits, presumably formed by turbidites in a similar manner, have been reported to occur basinward of the Bahama Banks (Newell, 1955, p. 307) and in deeper water northeast of the Yucatan carbonate complex (Davies, 1968, p. 1101-1106). Ancient graded carbonate beds have been described in the Permian limestones deposited basinward of the Captain Reef complex (Newell and others, 1953, p. 72).

### SOURCE OF RESEDIMENTED DETRITUS

Several lines of evidence indicate that the resedimented detritus in the pebbly mudstones, graded sandstones, and graded limestones in the Tetelna Complex was derived from the group of active volcanoes located to the west. First, as these resedimented deposits are the product of subaqueous gravity processes, the detritus must have been transported eastward down the paleoslope; it has already been argued that the paleoslope was linked directly to active volcanoes to the west. Secondly, a westerly source also is suggested by the facies patterns in the fence diagram in figure 3, especially in the Foggy Creek and Rainbow Ridge units. The pyroclastic and sedimentary strata in these members increase in thickness to the west, and lenses of sedimentary material wedge out in a northerly or northwesterly direction. Thirdly, because none of the resedimented deposits examined in thin section contains metamorphic or plutonic rock fragments, the source area must have been entirely volcanic in composition. The presence of pumice in some of the deposits is evidence that the source was an area of active volcanism. Finally, the volcanic rock fragments in the resedimented deposits and the lithic fragments in the pyroclastic deposits are quite similar in texture and in composition, implying derivation of both from the same source.

Most of the resedimented deposits probably were produced by slumping and avalanching of freshly erupted volcanic debris piled around the active vents. Some of the resedimented detritus also may have been produced by noneruptive processes such as crumbling of viscous lava flows and the collapse of domes and spines. Viscous flow breccias, domes, and spines are common products of effusive activity near vents erupting intermediate and acidic magma, and are well-known sources of lithic debris around subaerial volcanoes (Fisher, 1960, p. 974-978; Parsons, 1967, p. 178-180; Curtis, 1954, p. 461-471).

The abundance of fossil fragments in some of the resedimented deposits suggests that organic communities, possibly reefs or banks, developed in the source area (probably near the active volcanoes), and frequently contributed carbonate debris to the deeper parts of the environment by gravity processes. Because several small bioherms and biostromes occur in the Complex, some of the resedimented carbonate debris may also have been supplied by such carbonate bodies located on the flanks of the volcanoes seaward of the inferred reefs or banks.

## LIMESTONE DEPOSITS

### LIMESTONE TERMINOLOGY

The limestone nomenclature used here is based mainly on hand-specimen characteristics and is modified only where thin-section examination was made to supplement field and hand-specimen study. Deposits composed of reworked or transported carbonate debris (calcarenite or calcirudite) are called *bioclastic limestones* to distinguish them from bioherms and biostromes that consist of organic material essentially in place. The term *fine-grained limestone* (calcilutite) refers to limestone composed of mostly silt or mud-sized calcite. Many of the bioclastic limestones in the Tetelna Complex contain some volcanic detritus, but the amount of these impurities is never greater than 50 percent, and these rocks may be classified as impure bioclastic limestone.

### IMPURE BIOCLASTIC LIMESTONES

A relatively small but significant lens of bioclastic limestone with volcanic impurities occurs in the middle of the Foggy Creek unit in measured section 9 (pl. 2, fig. 3). Along the northern edge of the outcrop, the lens consists mainly of grayish, medium-bedded calcirudite, but it becomes finer grained southward; at its southernmost exposure it is a dark-gray, massive to medium-bedded calcarenite. The lens wedges out abruptly to the south and is replaced by fine-grained fossiliferous limestones.

The bioclastic wedge has a stratification, texture, and composition that contrast markedly with the rest of the formation. Most of the limestone—especially that in the southern part of the wedge—is moderately to well sorted, and in the northern part of the lens planar cross bedding, some with amplitudes of 1 to 2 feet, can be seen in a few exposures. Most of the noncarbonate impurities are moderately to well rounded. The detrital carbonate, volcanic rock fragments, and plagioclase are identical with those in the graded limestones, but the amount of detrital quartz is unusually high, ranging from 10 to 15 percent higher than in any other lithology in the formation.

The cross bedding, good sorting, rounding, and lack of stratification in this deposit suggest that, unlike most of the clastic deposits in the formation, this bioclastic lens was deposited from tractive currents. The deposit may have been produced by local bottom agitation that simply mixed indigenous carbonate debris with the sediment carried into the basin by turbidity currents. This seems unlikely, however, because the high quartz content in the deposit suggests that the noncarbonate fraction was derived from a different source than that which supplied the quartz-poor volcaniclastic detritus in the rest of the formation. This bioclastic lens probably was deposited from a bottom current that carried sediment with a high quartz content into the local area of deposition.

The evidence of tractive currents in this part of the Complex does not necessarily require that the depositional interface was, for a short period of time, elevated into the zone of wave agitation. Relatively deep bottom currents are known; for example, a current presently flows along the toe of the Mississippi River Delta at a depth of 400 feet and is depositing sediment on the margin of the deltaic complex with a composition foreign to that deposited by the Mississippi River (Scruton, 1960, p. 90).

The cross-bedded exposures are too few and too poorly exposed to obtain a statistically significant measure of current direction, but the southward decrease in grain size and the facies pattern (fig. 3) suggests that the current flowed along an axis trending roughly northeast-southwest.

Other lenses of impure bioclastic limestones, usually no greater than 3 to 5 feet thick, also occur in the formation, mostly in the Middle Ridge unit, but these are poorly sorted and quartz-poor. They were probably formed by the accumulation of carbonate debris within or on the margins of bioherms and biostromes, and mixing of the organic detritus with volcanic material was probably facilitated by burrowing activity.

### BIOHERMS AND BIOSTROMES

A few biohermal or mound-shaped masses of caninoid and lonsdaleoid corals occur in the middle part of the Foggy Creek unit (fig. 4). These mounds are small, ranging from 2 to 5 feet high and 5 to 20 feet long. The corals within these mounds are preserved in growth position, and the framework is usually filled with a bioclastic matrix locally containing fusulinids. The mounds themselves are surrounded by either bioclastic limestone or dark, fine-grained limestone.

All of the bioherms occur within a few feet stratigraphically above or below graded beds, and in at least one case, a small mass of corals is directly overlain by interbedded graded sandstones and claystones. These masses of corals apparently grew in quiet water below wave base.

Bedded organic deposits or biostromes occur mostly in the Foggy Creek and Middle Ridge strata (fig. 4). The biostromes are rarely more than 2 feet thick, and individual beds can be traced for at least 300 feet along outcrop surfaces. Some of the biostromes are composed of large caninoid corals embedded in a dark-gray calcilutite matrix. Others consist of spiriferid and productid brachiopods, commonly with delicate structures such as spines attached. The brachiopod biostromes occur in a dark calcilutite matrix in the Foggy Creek unit and in an impure bioclastic limestone in the Middle Ridge unit. Fenestrate and ramose bryozoans, embedded in a dark calcilutite, compose the third common type of biostrome, and these occur only in the lower part of the Foggy Creek strata.

Complete fossil collections were made from these limestones by R.L. Gilbertson, and a description of the faunal elements appears in his unpublished M.S. thesis, University of Wisconsin (1969).

### FINE-GRAINED LIMESTONES

Fine-grained limestone or calcilutite, found mainly in the Foggy Creek and Middle Ridge units (fig. 4), is the most common type of carbonate deposit in the formation. The calcilutite typically is thin-bedded or laminated, and is composed of silt-sized calcite and dolomite grains, and varying amounts of dark organic matter. The calcilutite is sparingly to abundantly fossiliferous, and contains a variety of spirifers, productids, corals, and bryozoans. The richly fossiliferous beds are mainly in the southern and eastern parts of the area, and unfossiliferous and silicified calcilutite predominates in the western part.

The occurrence of fossiliferous limestones in association with pebbly mudstones and flyschlike successions of graded beds may seem anomalous, but these associations are very common in the Tetelna Complex. One of the conclusions that may be drawn from this association is that the conditions favorable both for the growth of organic communities and for the formation of resedimentation phenomena such as graded beds and pebbly mudstones are not necessarily mutually exclusive within a sedimentary basin.

## MANKOMEN GROUP

A brief description of the Mankomen Group is given

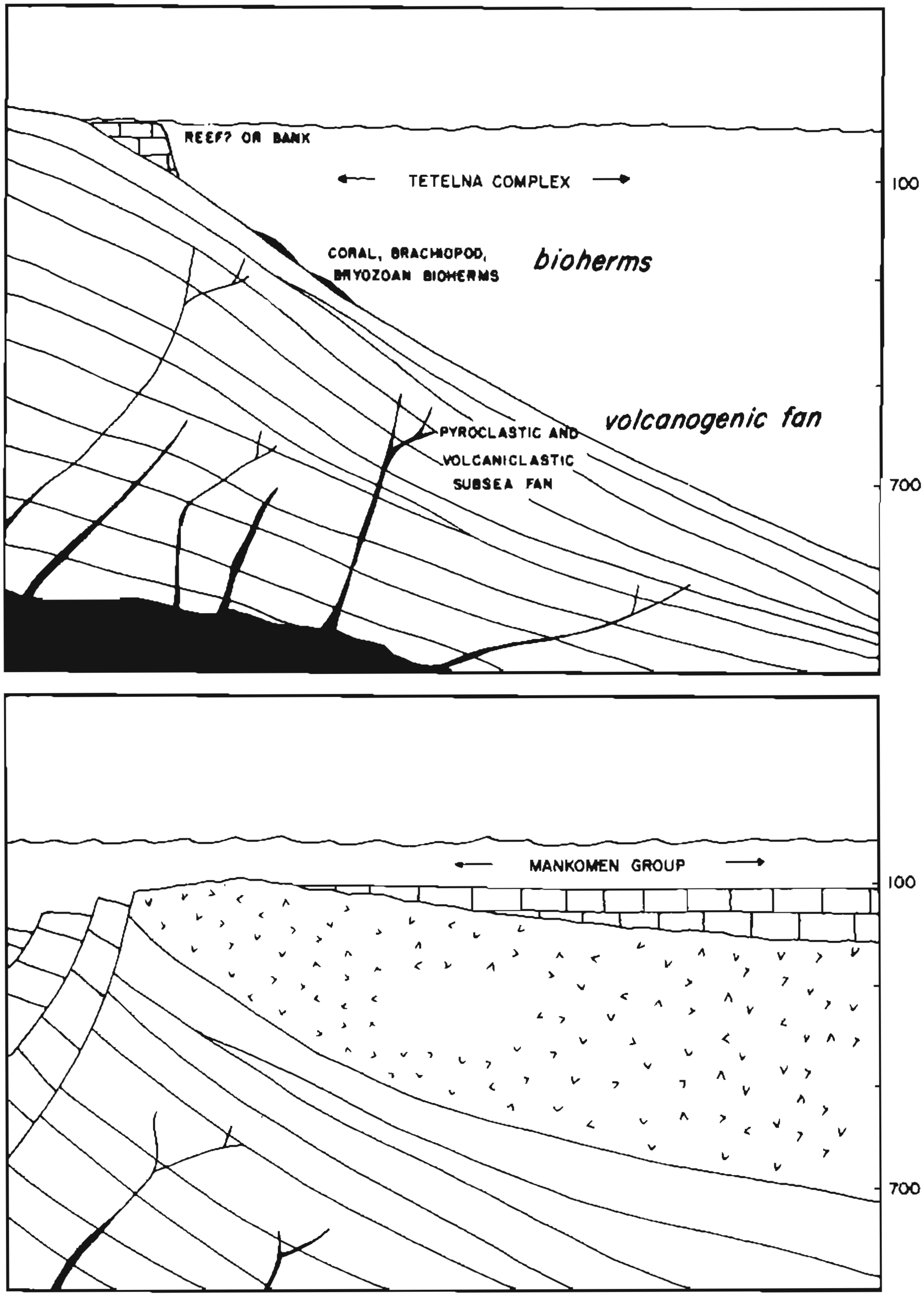


FIGURE 17.—Schematic representation of the change in environmental conditions for deposition of the Tetelna Complex and Mankomen Group.

lay to the south or southeast. The stratigraphy in each inferred subsea fan was controlled largely by the eruptive activity of each group of vents; consequently, the pyroclastic units within each fan are more or less continuous, as indicated in the western part of the area in figure 3. However, the pyroclastic stratigraphy cannot be matched from one fan to the other because of the somewhat different eruptive histories in the two groups of vents around which the fans were deposited. As is suggested in the central part of the diagram, coalescing of these subsea fans produced a complex interfingering of pyroclastic and sedimentary deposits at the fan margins.

Regional studies must be made in the area to test this hypothesis of fanlike deposition in the Tetelna Complex. However, similar deposition seems to have occurred recently in modern volcanic environments. For example, Menard (1964, p. 82-87) has called attention to the existence of broad, archipelagic aprons that have been deposited on the outer flanks of modern volcanic islands and island arcs in the Pacific Ocean. According to Menard, at least part of these aprons was deposited by turbidity currents carrying volcanically derived material away from the islands and into deeper water. The inferred subsea fans in the Complex may be similar in origin to modern archipelagic aprons.

## TRANSITION FROM EARLY TO MIDDLE WOLFCAMPIAN

Significant changes in paleogeography occurred between early and middle Wolfcampian time. The absence of pyroclastics and resedimented sandstones throughout the Mankomen Group indicates that by middle Wolfcampian time the volcanoes to the south and west became inactive and were no longer an important source of clastic material in the basin. In addition, the relatively deep environment in which most of the Tetelna Complex accumulated was replaced, at least for a short period of time, by a shallow, wave-agitated carbonate environment in which 200 feet of bioclastic limestone was deposited (fig. 17).

The erosional surface at the base of the Mankomen Group suggests that the strata in the map area may have been uplifted and eroded between early and middle Wolfcampian time. Subsidence may have followed this postulated uplift and produced the shallow depths in which the lower 200 feet of limestone in the Mankomen Group was deposited. During the postulated period of uplift and erosion, the volcanic source could have become extinct and deeply eroded, and when Mankomen sedimentation began, the volcanoes may not have been high enough to supply large amounts of volcanic debris to the basin. Rough time limits on the postulated period of erosion can be obtained by comparing the stratigraphic succession in the map area with the McCloud Formation (in California) that has subdivisions based on fusulinids that may be compared with the fusulinid zones in the Tetelna Complex and the Mankomen Group. In the McCloud Formation, nearly 2000 feet of strata occurs between fusulinid zones A and E (Skinner and Wilde, 1965, p. 13), the inferred faunal gap at the unconformity. Apparently there was sufficient time for considerable uplift and erosion to occur.

Nevertheless, the eruption of the exceptionally thick Bear Mountain lapilli tuff (unit Pbm), the disappearance of the volcanic source, and the change from a moderately deep to a relatively shallow environment could also have been the result of a single volcanic event. The inferred highly gaseous, paroxysmal eruption that produced the Bear Mountain lapilli tuff is the kind of eruption often accompanied by a major caldera collapse that can destroy much of the volcanic complex (Bullard, 1963, p. 75-91; Rittmann, 1962, p. 127-132; Williams, 1941, p. 253-265). The geologic history of Krakatoa is a familiar example (Williams, 1941, p. 253-265). Although it is largely speculation, the eruption of the Bear Mountain lapilli tuff may have been accompanied by a major caldera collapse that caused the rapid destruction of the local volcanic source or sources to the west and south. The period of volcanism in the source area may have ended at this time. The same event could account for the change in depositional environments in the basin of deposition. Since the eruption of the Bear Mountain lapilli tuff rapidly ejected a very large volume of pyroclastic material into the basin and produced a deposit at least 600 feet thick, it is reasonable to suppose that deposition of this pyroclastic unit caused a significant change in the water depth in the local marine environment. In fact, the sudden accumulation of this large volume of pyroclastic material may have nearly filled the basin and, in what was essentially a geologic instant, produced a shallow, wave-agitated platform where previously there had been a relatively deep, unagitated sea floor (fig. 17). The erosional surface and faunal gap at the top of the Bear Mountain member could have been produced by an extended period of subsea erosion and nondeposition before the Mankomen Group was deposited. Either of these two possibilities or a combination of both could be correct. However, in a sedimentary basin located near active volcanic vents, volcanism will have an important influence on sedimentation, and very rapid changes in paleogeography are to be expected.

## MIDDLE WOLFCAMPIAN

By middle Wolfcampian time, the shallow surface at the top of the Bear Mountain unit was rapidly populated by organic communities (fig. 17). Wave agitation and bottom currents distributed carbonate debris produced by these organisms over the surface of the platform, and a carbonate deposit about 200 feet thick accumulated before the environment became unsuitable for organic habitation (fig. 16). During the remainder of middle Wolfcampian time (as recorded by the Mankomen

Group in the vicinity of College Glacier), organic communities occasionally occupied the sea floor, perhaps during periods of uplift and shoaling, and produced a variety of carbonate deposits. Between these periods of organic habitation, the basin apparently was stagnant and possibly deeper, and only black silty claystone accumulated.

When the bioclastic limestone facies in the vicinity of College Glacier was accumulating, a source area composed of volcanics, chert, and metamorphic rocks contributed terrigenous detritus into the local environment. This source area must have been relatively nearby because the terrigenous rock fragments are locally as coarse as fine pebbles. The available data are not sufficient to determine the location of this source area.

## SUMMARY

A detailed study of the early Permian strata in part of the east-central Alaska Range strongly supports the hypothesis that a volcanic island archipelago, possibly similar to modern island arcs of the circumpacific type, is recorded in rocks of the eastern Alaska Range area. The location and trend of this chain is not yet known, but results of this study show that at least one group of upper Paleozoic volcanoes, probably islands, was located a short distance south of the present Alaska Range, a few miles west of the map area.

Volcanism apparently began near the area of investigation at least by middle Pennsylvanian time and perhaps earlier, and persisted until the end of the early Wolfcampian. Details of Pennsylvanian sedimentation are not known, but during early Wolfcampian time, deposition took place mostly below wave base in a moderately deep neritic environment, and sedimentation was almost entirely controlled by volcanism in the source to the west. Explosive eruptions produced subaqueous pyroclastic flows that repeatedly entered the marine environment and laid down thick successions of coarse, poorly sorted, unstratified lapilli tuffs. A large portion of the erupted debris also settled directly from eruption clouds to the sea floor, depositing well-stratified layers of tuff and lapillistone. Unstable masses of volcanic debris that were piled around the volcanoes frequently slumped and flowed into the area as subaqueous mud flows and turbidity currents. These processes deposited numerous beds of pebbly mudstones and graded sandstones. During periods of volcanic quiescence, lenticular limestone deposits accumulated (many of which consist of coral, brachiopod, and bryozoan bioherms and biostromes). Numerous carbonate turbidites interbedded with the volcanic sediments suggest that organic communities, possibly reefs, populated shallow areas around the postulated volcanic islands. Volcanism in the source area to the west may have ended with a cataclysmic eruption of the Krakatoan type, and the eruption may have been accompanied by a caldera collapse. The rapid accumulation of over 600 feet of pyroclastic debris produced by this eruption may have partly or completely filled the local marine environment.

By middle Wolfcampian time, after a relatively brief period of either erosion or nondeposition or both, the limestone and black shales of the Mankomen Group were deposited. The limestones were deposited mainly above wave base by tractive currents that distributed carbonate shell debris over the platform constructed by the preceding period of volcanism. Although the strata of the Mankomen Group are no younger than Wolfcampian in the area of investigation, stratigraphic studies completed elsewhere in the eastern Alaska Range suggest that limestone and black-shale deposition in the region continued throughout most of the Permian.

## REFERENCES CITED


American Commission on Stratigraphic Nomenclature, 1961, Code of stratigraphic nomenclature: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 645-665.

Aubouin, J., 1965, Geosynclines: Elsevier Pub. Co., Amsterdam, 335 p.

Bigelow, H.B., and Edmondson, W.T., 1947, Wind waves at sea; breakers and surf: U.S. Navy Dept. Hydrographic Office, Publ. no. 602, 177 p.

Bond, G.C., 1965, Bedrock geology of the Gulkana Glacier area, east-central Alaska Range, Alaska: M.S. thesis, Univ. of Alaska, College, Alaska, 44 p.

—— 1969, Permian volcanics, volcaniclastics, and limestones in the Cordilleran eugeosyncline, east-central Alaska Range, Alaska: Ph. D. thesis, Univ. of Wisconsin, Madison, Wisconsin, 144 p.

—— 1974, A late Paleozoic volcanic arc in the eastern Alaska Range, Alaska: Jour. Geology, v. 81, p. 557-576.

Bouma, A.H., 1962, Sedimentology of Some Flysch Deposits: Elsevier Pub. Co., Amsterdam, 168 p.

Brew, D.A., Loney, R.A., and Muffler, L.J., 1966, Tectonic history of southeastern Alaska, *in* A symposium on the tectonic history and mineral deposits of the Western Cordillera, British Columbia, and neighboring parts of the United States: Canadian Inst. Mining and Metallurgy, Spec. Vol. 8, p. 149-170.

Bullard, F.M., 1963, Volcanoes, in History, in Theory, in Eruption: Univ. of Texas Press, Austin, Texas, 441 p. (3rd edition).

Cady, W.M., Wallace, R.E., Hoare, J.M., and Webber, E.J., 1955, The central Kuskokwim region, Alaska: U.S. Geol. Survey Prof. Paper 268, 132 p.

Carlisle, D., 1963, Pillow breccias and their aquagene tuffs, Quadra Island, British Columbia: Jour. Geology, v. 71, p. 48-71.

Cloud, P.E., Schmidt, R.G., and Burke, H.W., 1956, Geology of Saipan, Mariana Islands: pt. 1, General Geology: U.S. Geol. Survey Prof. Paper 280 A, 126 p.

Crowell, J.C., 1957, Origin of pebbly mudstones: Geol. Soc. America Bull., v. 68, p. 993-1010.

Curtis, G.H., 1954, Mode of origin of pyroclastic debris in the Mehrten Formation of the Sierra Nevada: Univ. of Calif., Dept. Geol. Sci. Bull., v. 29, p. 453-502.

Curtis, G.H., 1964, The stratigraphy and ejecta from the 1912 eruption of Mount Katmai and Novarupta, Alaska, *in* Studies in Volcanology: Geol. Soc. America Mem. 116, p. 153-210.

Davies, D.K., 1968, Carbonate turbidites, Gulf of Mexico: Jour. Sedimentary Petrology, v. 38, p. 1100-1109.

Detterman, R.L., and Reed, B.L., 1964, Preliminary map of the geology of the Iliamna quadrangle, Alaska: U.S. Geol. Survey Misc. Geol. Inv. Map I-407, scale 1:250,000.

Dietz, R.S., 1963, Collapsing continental rises: an actualistic concept of geosynclines and mountain building: Jour. Geology, v. 71, p. 314-334.

Donnelly, T.W., 1966, Geology of St. Thomas and St. John, U.S. Virgin Islands, *in* Hess, H.H. (ed.), Caribbean Geological Investigations: Geol. Soc. America Mem. 98, p. 85-178.

Dott, R.H., 1963, Dynamics of subaqueous gravity depositional processes: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 104-128.

Dzulynski, S., Ksiazkiewicz, M., and Kuenen, Ph.H., 1959, Turbidites in flysch of the Polish Carpathian Mountains: Geol. Soc. America Bull., v. 70, p. 1089-1118.

Dzulynski, S., and Walton, E.K., 1965, Sedimentary features of flysch and greywackes, *in* Developments in Sedimentology, no. 7: Elsevier Pub. Co., Amsterdam, 274 p.

Eardley, A.J., 1962, Structural Geology of North America: Harper and Row, Inc., New York (2nd edition).

Fisher, R.V., 1960, Classification of volcanic breccias: Geol. Soc. America, v. 71, p. 973-982.

———1965, Settling velocity of glass shards: Deep-Sea Research, v. 12, p. 345-353.

———1966, Rocks composed of volcanic fragments and their classification: Earth-Science Reviews, v. 1, p. 247-286.

Fiske, R.S., 1963, Subaqueous pyroclastic flows in the Ohanapecosh Formation, Washington: Geol. Soc. America Bull., v. 74, p. 391-406.

———1964, Submarine equivalents of ash flows in the Tokina Formation, Japan: Am. Jour. Sci., v. 262, p. 76-106.

———1969, Recognition and significance of pumice in marine pyroclastic rocks: Geol. Soc. America Bull., v. 80, p. 1-8.

Gilbertson, R.L., 1969, Biostratigraphy of the upper Paleozoic rocks in the Gulkana Glacier area, Alaska: M.S. thesis, Univ. of Wisconsin, Madison, Wisconsin, 43 p.

Grantz, A., 1968, Strike slip faults in Alaska (Abstract): Geol. Soc. America, 1968 Annual Meeting, Mexico City.

Hanson, B.M., 1957, Middle Permian limestone on Pacific side of Alaska Peninsula: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 2736-2738.

Hanson, L.G., 1964, Bedrock geology of the Rainbow Mountain area, Alaska Range, Alaska: Alaska Div. of Mines and Minerals, Geol. Rept. 2, 82 p.

Hoare, J.M., 1961, Geology and tectonic setting of lower Kuskokwim-Bristol Bay region, Alaska: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 594-611.

Lanphere, M.A., and Reed, B.L., 1973, Timing of Mesozic and Cenozoic plutonic events in circum-Pacific North America: Geol. Soc. America Bull., v. 84, p. 3773-3782.

Luders, K., 1955, Sediments of the North Sea, *in* Trask, P.D. (ed.), Recent Marine Sediments (a symposium): Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 4, p. 322-342.

McBride, E.F., 1962, Flysch and associated beds of the Martinsburg Formation (Ordovician), Central Appalachians: Jour. Sedimentary Petrology, v. 32, p. 39-91.

McGugan, A., Roessingh, H.K., and Danner, W.R., 1965, The Permian, *in* McCrassan, R.G. and Glaister, R.P. (eds.), Geologic History of Western Canada: Alberta Soc. Petroleum Geologists, Calgary, Alberta, p. 103-112.

Mackevett, E.M., Jr., 1969, Nikolai Greenstone of Wrangell Mountains near Kennicott, Alaska, *in* Abstracts for 1969: Geol. Soc. America Spec. Paper 82, p. 261.

Matteson, C., 1973, Bedrock geology of the Slate Creek-Middle Fork Chistochina area, eastern Alaska Range, Alaska: M.S. thesis, Univ. of Alaska, College, Alaska.

Menard, H.W., 1964, Marine Geology of the Pacific: McGraw-Hill Book Co., 271 p.

Mendenhall, W.C., 1900, A reconnaissance from Resurrection Bay to the Tanana River, Alaska, in 1898: U.S. Geol. Survey, 20th Ann. Rept. for 1898-99, pt. 7, p. 265-340.

———1905, Geology of the central Copper River region, Alaska: U.S. Geol. Survey Prof. Paper 41, 133 p.

Miller, D.J., and MacColl, R.S., 1964, Geologic map and sections of the northern part of the McCarthy A-4 quadrangle, Alaska: U.S. Geol. Survey Misc. Geol. Inv. Map I-410, scale 1:250,000.

Moffit, F.H., 1912, Headwater regions of the Gulkana and Susitna Rivers, Alaska: U.S. Geol. Survey Bull., v. 498, 82 p.

———1954, Geology of the eastern part of the Alaska Range and adjacent area: U.S. Geol. Survey Bull. 989-D, 218 p.

Murai, I., 1961, A study of the textural characteristics of pyroclastic flow deposits in Japan: Earthquake Res. Inst. Bull., v. 39, p. 133-248.

Newell, N.D., Rigby, J.K., Fischer, H.G., Whiteman, A.J., Hickox, J.E., Bradley, J.S., et al., 1953, The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico: W.H. Freeman and Co., San Francisco, 353 p.

———1955, Bahamian platforms, *in* Poldervaart, A. (ed.), Crust of the Earth (a symposium): Geol. Soc. America, Spec. Paper 62, 762 p.

Onions, D., and Middleton, G.V., 1968, Dimensional grain orientation of Ordovician turbidite greywackes: Jour. Sedimentary Petrology, v. 38, p. 164-175.

Parsons, W.H., 1967, Manner of emplacement of pyroclastic andesitic breccias: Bull. Volcanol., v. 30, p. 177-187.

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

Petocz, R.G., 1967, Preliminary observations on fusulinidae from the east-central Alaska Range: Jour. Paleontology, v. 41, p. 1547-1549.

Potter, P.E., and Mast, R.F., 1963, Sediment structures, sand-shaped fabrics, and permeability, pt. 1: Jour. Geology, v. 71, p. 441-471.

Ragan, D.M., and Hawkins, J.W., Jr. 1966, A polymetamorphic complex in the eastern Alaska Range: Geol. Soc. America Bull., v. 77, p. 597-604.

Richter, D.H., 1966, Geology of the Slana district, south-central Alaska: Div. of Mines and Minerals Geol. Rept. 21, 51 p.

—— and Jones, D.L., 1973, Structure and stratigrapby of eastern Alaska Range, Alaska, *in* Pitcher, M.G. (ed.), Arctic Geology: Am. Assoc. Petroleum Geologists Mem. 19, p. 408-420.

Rittmann, A., 1962, Volcanoes and Their Activity: John Wiley and Sons, Inc., New York, 305 p. (1st ed.).

Rose, A.W., 1965, Geology and mineral deposits of the Rainy Creek area, Mt. Hayes quadrangle, Alaska: Alaska Div. of Mines and Minerals Geol. Rept. 14, 41 p.

——1967, Geology of the Upper Chistochina River area, Mt. Hayes quadrangle, Alaska: Alaska Div. of Mines and Minerals Geol. Rept. 28, 37 p.

Ross, C.S., and Smith, R.L., 1960, Ash flow tuffs: their origin, geologic relations, and identifications: U.S. Geol. Survey Prof. Paper 366, 98 p.

Rowett, C.L., 1969, Upper Paleozoic stratigraphy and corals from the east central Alaska Range, Alaska: Arctic Inst. of North America Tech. Paper No. 23, 120 p.

Schwarzacher, W., 1951, Grain orientation in sands and sandstone: Jour. Sedimentary Petrology, v. 21, p. 162-172.

Scruton, P.C., 1960, Delta building and the deltaic sequence, *in* Shepard, F.P., Phleger, F.B., and van Andel, T.H. (eds.), Recent sediments, northwest Gulf of Mexico: Am. Assoc. Petroleum Geologists, p. 32-381.

Sigvaldason, G.E., 1968, Structure and products of subaquatic volcanoes in Iceland: Contributions Mineralogy and Petrology, v. 18, p. 1-16.

Skinner, J.W., and Wilde, G.L., 1965, Permian biostratigraphy and fusulinid faunas of the Shasta Lake area, Northern California: Univ. of Kansas Paleontology Contributions, Art. 6, p. 1-98.

Smith, P.S., 1939, Areal geology of Alaska: U.S. Geol. Survey Prof. Paper 192, 100 p.

Smith, T.E., and Turner, D.L., 1973, Geochronology of the Maclaren metamorphic belt, south-central Alaska: a progress report: Isochron/West, no. 7, p. 21-25.

St. Amand, P., 1957, Geological and geophysical synthesis of the tectonics of portions of British Columbia, the Yukon territory, and Alaska: Geol. Soc. America Bull., v. 68, p. 1343-1370.

Stetson, H.C., 1955, Summary of sedimentary conditions on the continental shelf of the east coast of the United States, *in* Trask, P.D. (ed.), Recent Marine Sediments (a symposium): Soc. Econ. Paleontologists and Mineralogists, Spec. Publ. 4, 736 p.

Stout, J.H., 1965, Bedrock geology between Rainy Creek and the Denali Fault, eastern Alaska Range, Alaska: M.S. thesis, Univ. of Alaska, College, Alaska, 75 p.

Sverdrup, H.V., Johnson, N.W., and Fleming, R.H., 1942, The Oceans, Their Physics, Chemistry, and General Biology: Prentice-Hall, Inc., New York, 1087 p.

Teichert, C., 1958, Cold- and deep-water coral banks: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 1064-1082.

Tracey, J.I., Schlanger, J.O., Stark, J.T., Doan, D.B., and May, H.G., 1964, General geology of Guam: U.S. Geol. Survey Prof. Paper 403-A, 104 p.

Unklesbay, A.G., and Pauken, R., 1966, Pennsylvanian ammonoids from Alaska: Jour. Paleontology, v. 40, p. 1379-1380;

van Bemmelen, R.W., 1949, The Geology of Indonesia, v. 1A: Martinus Nijhoff, The Hague, 732 p.

Walker, R.G., and Sutton, R.G., 1967: Quantitative analysis of turbidites in the Upper Devonian Sonyea Group, New York: Jour. Sedimentary Petrology, v. 37, p. 1012-1022.

Well, J.W., 1967, Corals as bathometers: Marine Geology, v. 5, p. 349-367.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Jour. Geology, v. 30, p. 377-392.

——1926, Pyroclastic geology of Oahu: B.P. Bishop Mus. Bull., v. 30, p. 55-60.

Wheeler, H.E., 1940, Permian volcanism in western North America: Pacific Sci. Cong., 6th, 1939, Proc., v. 1, p. 369-376.

Wheeler, J.O., 1961, Whitehorse map-area, Yukon Territory: Geol. Survey of Canada Mem. 312, 156 p.

Whetten, J.T., 1966, Geology of St. Croix, U.S. Virgin Islands, *in* Hess, H.H. (ed.), Carribbean Geological Investigations: Geol. Soc. America Mem. 98, p. 177-239.

Williams, H., 1926, Notes on the characters and classification of pyroclastic rocks: Geol. Soc. Liverpool, Proc., v. 14, p. 223-248.

——1941, Calderas and their origin: Univ. Calif. Pub., Dept. of Geol. Sci., v. 25, p. 239-346.

# APPENDIX I - MEASURED STRATIGRAPHIC SECTIONS[1]

## SECTION 1

Section begins on southeast side of College Creek at lowest exposure of beds immediately east of a small north-trending gully in the valley wall. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Foggy Creek (map unit Pfc)* | | |
| 1. | Thin- to medium-bedded, light-green to greenish-gray fine tuffs and tuffaceous claystone-siltstone. Some tuffs are slightly limey with some contemporaneous deformation. A few beds of sandstone and conglomerate occur, some of which are graded. These beds probably have a tuffaceous matrix. | 42 |
| 2. | Andesitic to dacitic lapilli tuff. The deposit is mostly crystal-vitric, but has some layers of lithic debris. | 40 |
| 3. | Interbedded green to greenish-gray graded sandstones, fine tuffs and tuffaceous claystone-siltstone. | 25 |
| 4. | Light-green dacite lithic-crystal lapilli tuff. Characterized by abundant quartz. Also contains abundant fossil clasts including corals and brachiopods. In addition, clasts of black claystone rip-ups are common. Becomes finer-grained near top. | 50 |
| 5. | Covered. | 35 |
| *McCallum Creek (map unit Pmc)* | | |
| 6. | Interbedded black to gray claystone-siltstone and graded sandstones. A few coarse crystal-lithic tuffs less than 10 feet thick also are present. Sandstones are composed entirely of volcanically derived lithic and crystal material. | 246 |

## SECTION 2

Section begins at the bottom of the north Hoodoo on the northwest side at the base of the lowest exposed strata. At the top of interval 1, the section shifts to the south Hoodoo and continues up stratigraphically in the small gully between the two Hoodoos.

| Interval | Lithology | Thickness |
|---|---|---|
| *Part of the upper Mankomen Group (map unit $Pml_2$)* | | |
| 1. | Light-gray to yellowish-gray bioclastic to biohermal limestone. Bedding is thin to medium. Limestone consists mainly of bryozoa, many of which are nearly completely preserved. Some colonies appear to be in growth position, but most tend to lie flattened in the plane of bedding. Most of the bryozoa show little evidence of abrasion, and the skeletons have undergone little, if any, transport. The bedding tends to be irregular or wavy, largely because of the abundance of irregular masses of bryozoa. | 20 |
| 2. | Medium- to light-gray massive beds of bioclastic limestone. Close examination may show thin to medium bedding in places, but this appears to be obscured in most of the interval because of extensive recrystallization. From a distance, bedding is defined by prominent ledges 10 to 15 feet thick. The limestone consists mainly of crinoidal debris and small pieces of bryozoa skeleton, many of which are flattened in the plane of bedding. Grain size appears to vary throughout the interval; some beds are calcirudite, others are fine-grained calcarenite. Sorting also varies; some beds of crinoidal debris are well sorted, other layers consist of fossil debris 'floating' in a calcilutite matrix. | 260 |
| 3. | Light-gray to yellowish-gray medium- to thick-bedded bioclastic limestone, mostly calcarenite. Numerous beds and lenses of terrigenous siltstone, sandstone, and fine pebble conglomerate are scattered throughout the interval. The terrigenous material is well sorted and usually mixed | |

1. All thicknesses in feet

| | | |
|---|---|---|
| | with about 10 to 40 percent bioclastic detritus. Some of the thicker beds of terrigenous sediment are cross bedded; cross-bed sets are 6 to 18 inches high, and the cross stratification is planar to slightly trough-shaped. The beds of terrigenous material range in thickness from a few inches to 3 feet. Except for the presence of terrigenous sediment, the limestone is similar to that in interval 2. | 40 |

*Part of the upper Mankomen Group (map unit $Pma_2$)*

| | | |
|---|---|---|
| 4. | Interval 3 is abruptly overlain by nonfissile black to dark-gray mudstone or argillite. Bedding ranges from thin to medium. A few thin laminae of white fine tuff occur within parts of the interval. These laminae are nearly always less than 1 inch thick. No fossils were found in the interval. | 200? |

## SECTION 2A

The section begins above the moraine on the north side of the College Creek Valley in a small gully at the base of the prominent white limestone ledge. The section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Part of the upper Mankomen Group (map unit $Pma_1$)* | | |
| 1. | Light-gray to white massive bioclastic limestone. Bedding not generally apparent but is probably thick to massive. A crude stratification is defined in places by alignment of elongate bryozoa fragments. A few crinoid columnals are evident on some outcrop surfaces. Most of the limestone is severely recrystallized; some parts appear to be marble. Lenses and pods of chert are common in parts of the interval. The base of the limestone is not exposed. | 50 |
| 2. | Dark-gray to black nonfissile claystone or mudstone. Grain size in places may range up to siltstone. Parts of interval are highly indurated and approach an argillite or slate. No limey beds or fossils observed. | 45 |
| 3. | Interbedded gray to greenish-gray siltstone, light-gray bioclastic limestone, and silty, muddy limestone, generally gray to orange gray. Bedding is thick to medium. A few lenses of chert or silicified limestone occur in parts of the interval. | 80 |
| 4. | A succession of strata similar to interval 2. | 150 |
| 5. | Interbedded black to dark-gray silty or muddy limestone, gray-green siltstone to fine sandstone, and black mudstone or argillite. Abundant fossils occur in this interval, especially in the upper part. The fossils are mostly brachiopods and bryozoa. Bedding is thick to medium and in many places appears to be wavy or lenticular. Much of this interval is highly fractured and intruded by gabbroic sills and dikes. | 700 |

## SECTION 5

Section begins near crest of ridge at Mankomen Group--Bear Mountain lapilli tuff (unit Pbm) contact. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Lower Mankomen Group (map unit $Pml_1$)* | | |
| 1. | Mostly thin- to medium-bedded calcilutite; weathers brownish gray, medium gray fresh. Small pods of chert and silicified patches common. Fossils are mostly corals and brachiopods, scattered or floating in the fine matrix. Section line broken and shifted about 300 feet west between this and the next interval. | 41 |
| 2. | Medium-bedded calcarenite to calcirudite; weathers brown, light gray fresh. Deposit contains mixture of bryozoa, crinoid, and brachiopod debris, giving a fresh surface a black-and-white speckled appearance. | 2 |
| 3. | Medium-bedded calcilutite; weathers dark-brownish gray, medium gray fresh. Pods of chert locally present. Large rugose corals and brachiopods occur scattered or floating in the matrix. | 39 |

| | | |
|---|---|---|
| 4. | Gabbroic sill. | 3 |
| 5. | Medium- to thin-bedded calcirudite; weathers dull gray, light gray fresh. Abundant crinoidal debris. A few poorly preserved brachiopods and broken coral present also. | 9 |
| 6. | Medium- to thin-bedded calcarenite; weathers brownish gray, light gray fresh. Mixture of dark- and light-colored fossil clasts gives deposit a speckled appearance. Pods of chert present locally. Crinoid debris and brachiopods are abundant. | 17 |
| 7. | Medium- to thin-bedded calcilutite; weathers brown, medium to dark gray fresh. Brachiopods occur floating in matrix. Stringers and pods of chert are common. | 8 |
| 8. | Medium- to thin-bedded calcirudite; light gray weathered, medium gray fresh. Contains abundant crinoids, with lesser amounts of brachiopod fragments (mostly broken). Locally abundant stringers of chert and cherty calcirudite occur also. | 5 |
| 9. | Calcarenite - essentially the same as interval 7. | 27 |
| 10. | Distinct, white recrystallized limestone adjacent to a gabbro dike. | 8 |
| 11. | Medium-bedded calcarenite to calcirudite; weathers gray, light gray fresh. Mostly crinoidal limestone with minor lenses of chert. | 21 |
| 12. | Mostly medium-bedded dark-gray calcilutite with abundant masses of chert and cherty limestone. Scattered fossils, mostly corals and brachiopods. Amount of terrigenous clay and silt increases markedly in upper 23 feet of interval. In the uppermost part of the interval are thin layers of black limey shale. Some bioturbation can be seen in shaley layers. | 31 |

## SECTION 6

Section begins at the stream level of the northeasternmost exposure and extends downstream to the point where the base of a prominent limey unit (3) reaches stream level; section then breaks and continues along valley wall in direction of dip of strata. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Part of Middle Ridge (map unit Pmr)* | | |
| 1. | Several internally stratified lapilli tuffs and coarse tuffs, green to grayish green. Mostly crystal tuffs, but lithic tuffs also are present. All are distinctly graded from coarse tuff to lapilli at base to fine or coarse tuff at top. Pumice is abundant in parts of the tuffs; the pumice clasts typically are dark green, platelike fragments flattened in the plane of stratification. Double grading is the most dominant type of internal stratification. The tuffs in the highest part of the section are slightly limey and contain broken fragments of crinoid columnals. | 108 |
| 2. | Coarse breccia, massively bedded, dark, and composed almost entirely of angular, andesitic volcanic clasts. Also contains a few fossils---mostly spiriferoid brachiopods. | 4 |
| 3. | Interbedded limey coarse tuffs, limey lapilli tuffs, limey siltstones, and thin stringers of calcarenite containing volcanic detritus. Abundant brachiopods on some bedding planes. *Plicatifera* sp. are also present. Many tuffaceous beds have a distinctive yellowish color due to abundance of epidote. | 152 |

## SECTION 10

Section begins in the lowest exposed strata on the north side of the ridge and extends up the ridge in the direction of dip. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *North Cirque (map unit Pnc) - probably middle and upper part.* | | |
| 1. | Several doubly graded lithic lapilli tuffs. Thickness of the individual tuffs varies from less than 2 feet to over 50 feet. Coarse lithic material occurs at the base of most of the deposits; this grades upward into stratified lapilli tuff and coarse tuff in which crystal debris typically predominates over lithic material. Lithic clasts are fine-grained to porpyritic red, maroon, green, and white volcanic rock fragments. Some of the banded layers are a distinct yellow-green, | |

| | | |
|---|---|---|
| | probably due to abundance of epidote. Pumice is abundant throughout the deposits and has altered to chloritic minerals giving the deposits a green to dark-green color. | 260 |
| *Middle Ridge (map unit Pmr)* | | |
| 2. | Interbedded bioclastic limestones with volcanic debris, doubly graded lithic lapilli tuffs, limey siltstones, claystones, and graded sandstones. Color of the various deposits varies from green to brownish green, depending largely on the carbonate content. The tuffs range up to 30 feet thick. The bioclastic limestones are minor components of the lithology and generally contain large amounts of lithic, crystal, and pumiceous volcanic debris. Most of the fossils in the siltstones and graded sandstones are crinoid columnals, brachiopods, and a few rugose corals. Bedding ranges from thin to medium in the sediments. | 250 |
| *Lower part of Rainbow Ridge (map unit Pr)* | | |
| 3. | Several green to light-green doubly graded lapilli tuffs and lapillistones. The tuffs are mostly crystal-vitric with abundant greenish pumice, plagioclase, and a small amount of quartz. The light-green color of these tuffs clearly distinguishes them from the darker green lithic lapilli tuffs in the underlying North Cirque unit. Individual pyroclastic deposits are as much as 30 feet thick. | 93 |

## SECTION 12

Section begins on the south side of the east-trending gully at the lowest exposure of strata. Section is measured stratigraphically up.

| Interval | Lithology | Thickness |
|---|---|---|
| *Upper part of Middle Ridge (map unit Pmr)* | | |
| 1. | Green tuffaceous siltstones and graded sandstones. Bedding varies from thin to medium. Interval also contains a few thin white layers of fine tuff. The clasts in the sandstones are prodominantly lithic volcanic material. | 75 |
| 2. | Thin- to medium-bedded limestone, limey siltstones, and graded lithic sandstones. Colors range from gray to brown to green, depending on the barbonate content. Large productid and spiriferoid brachiopods commonly occur on bedding planes in the more limey units and in the limestones. The limestones contain an admixture of volcanically derived lithic debris. | 86 |
| | Possible fault. | |
| *Middle part of the Rainbow Ridge (map unit Pr)* | | |
| 3. | Interbedded silicified claystones, siltstones, graded sandstones and fine pebble conglomerates, and coarse tuffs to lapilli tuffs. The sedimentary material is much more abundant than the pyroclastic rocks. Colors range from green to greenish white to maroon in some of the graded beds. All of the sedimentary deposits are tuffaceous. Most of the graded beds are less than 1 foot thick. | 204 |
| | Possible fault. | |
| 4. | Lower part of this interval is a dacite lapillistone, 22 feet thick, light to medium gray. A distinct pumiceous layer occurs at the top of the deposit. Rest of interval consists of interbedded black to dark-brown silicified claystone, thin graded lithic sandstones and conglomerates, and a few fossiliferous limestones containing brachiopods and corals. Many of the limestone beds are argillaceous. Also, a few thin coarse tuffs, mostly dacitic in composition, are scattered throughout the interval. | 197 |
| 5. | Mostly thin- to medium-bedded bioclastic limestones. Color ranges from light gray to brown. In places, the limestones contain abundant coral and brachiopod faunas; most of these are not in growth position but are not significantly abraded. The distance the organisms were transported appears to have been short. Most of the limestones contain inclusions of black claystone similar to that in the underlying interval. There are also some inclusions of lithic volcanic | |

| | | |
|---|---|---|
| | debris. Other lithologies in this interval are brown limey siltstones, thin dacitic coarse tuffs, and graded sandstones to fine pebble conglomerates. | 127 |
| 6. | Light-green to gray dacitic lapillistones and lapilli tuffs. Probably all are part of a single major eruption. Most of the deposit is well stratified. Pumice is abundant and scattered throughout the interval. Crystals consist of plagioclase and 10 to 20 percent quartz. Lithic fragments are rare but occur in scattered lenses in parts of the interval. The most common lithic clasts are ellipsoidal-shaped masses of black claystone identical to the black claystones that occur in the underlying strata in interval 4. | |

## SECTION 13

Section begins on the northeast side of the ridge at the bottom of the sedimentary section that overlies the purplish intrusive breccia exposed above the morainal deposits. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Lower part of North Cirque (map unit Pnc)* | | |
| 1. | Several green to dark-green lithic lapilli tuffs. Most of these are doubly graded. Lithic clasts are greenish to purplish basaltic-andesitic fragments with textures ranging from porphyritic to fine grained. Crystals consist of plagioclase; no quartz was observed in hand specimen. Pumice is abundant and occurs throughout each deposit. The pumice is flattened in the plane of bedding. Fossil clasts occur in the base of some of the pyroclastic deposits and one of the coarser deposits contains a block of limestone 8 feet long and 3 feet wide. | 240 |
| *Middle Ridge (map unit Pmr)* | | |
| 2. | Interbedded green to brownish-green claystone, siltstone, and graded sandstone to fine pebble conglomerate, many of which are limey and fossil bearing. Bedding is thin to medium. Some cross bedding occurs in parts of the interval. The graded sandstones and conglomerates are mostly composed of lithic volcanic fragments and plagioclase. A few thin beds of tuffaceous limestones are also present in part of the interval. These beds are highly fossiliferous in places. The fossils are mostly brachiopods. | 120 |
| *Rainbow Ridge (map unit Pr)* | | |
| 3. | Interbedded green to light-green crystal vitric lapilli tuffs and lapillistones. Most are doubly graded. A distinct white-and-green banding characterizes the upper part of the doubly graded beds. Pumice is abundant in the deposits and usually is flattened in the plane of bedding. Crystals consist of plagioclase and a small amount of quartz. Silicified bluish-gray siltstones and claystones are interbedded with the pyroclastics, but are not as abundant as the tuffs. Most of these claystones-siltstones are tuffaceous and many contain pumice clasts. | 53 |
| 4. | Interbedded green, bluish-gray, and purplish claystone, siltstone and graded sandstone to fine pebble conglomerate. Beds range in thickness from a few inches to about 2 feet. A few lapilli tuffs and lapillistones also occur but they are not as abundant as those in interval 3. In the upper part of this interval are a few beds of limestone---generally less than 1 foot thick. Some of the limestones contain brachiopod, coral, and fusulinid fossils. Clasts in the graded beds consist of a mixture of plagioclase and lithic debris of volcanic composition. | 124 |
| 5. | At least four crystal-vitric lapilli tuffs; green to light green and doubly graded. Lower parts of the tuffs are lithic-rich; the upper parts are crystal-vitric and banded with layers ranging from green to white. Crystals consist of plagioclase and a small amount of quartz. | 16 |

## SECTION 17

Section begins on the north side of the ridge at the stratigraphically lowest calcareous bed and extends up and over ridge crest.

| Interval | Lithology | Thickness |
|---|---|---|
| *Upper part of Middle Ridge (map unit Pmr)* | | |
| 1. | Green to brownish-green tuffaceous claystones and siltstones, many of which are calcareous. Mostly thin to medium bedded, but some have internal laminations. A few siltstones contain scattered pebble-sized clasts of volcanic composition. Sorting generally is poor. The siltstones and claystones are interbedded with graded sandstones and fine pebble conglomerates that occur in beds ranging from a few inches to 2 feet thick. The graded beds range in composition from feldspathic to lithic sandstones; the lithic debris is entirely volcanic. Color of the graded beds varies from greenish to purplish. | 30 |
| 2. | Medium-gray coarse-grained bioclastic limestones with scattered volcanic debris, siltstone rip-ups, and pumice clasts. Abundant fossils---consisting of mostly corals and brachiopods---occur in places. Bedding ranges from medium to thick. | 29 |
| 3. | Mostly a succession of strata very similar to interval 1 but contains a greater number of calcareous beds and also a few relatively pure limestone layers usually less than 1 foot thick. Abundant brachiopod and coral fossils occur in the limestones and in some of the siltstones. | 9 |
| 4. | Interbedded green to purplish siltstones, sandstones, and fine pebble conglomerates, most of which are graded. Most of the deposits appear to have a tuffaceous matrix. | 34 |
| 5. | Succession of strata similar to interval 3. Abundant fossils---mostly brachiopods and corals---in many of the beds. | 44 |
| 6. | Dark-green doubly graded lithic lapilli tuff. Largest lithic clasts about 1 to 2 inches in diameter. Deposit contains abundant pumice and feldspar in addition to lithic debris. Probably andesitic, as quartz is not evident in hand specimen. | 11 |
| 7. | Interbedded greenish to brownish calcareous siltstones and graded sandstones, most of which are lithic. | 8 |
| 8. | Single bed of bioclastic limestone with fine pebble-sized clasts of volcanic debris at base of deposit. A crude grading is evident in the upper part of the bed because of reduction in size of the carbonate debris. Fossils are abundant, and consist mainly of brachiopods, corals, and gastropods. | 10 |
| 9. | Several graded beds of bioclastic limestone similar in composition to intervals 8 and 2. Graded limestones range from 3 to 5 feet thick. | 24 |
| *Rainbow Ridge (map unit Pmr)* | | |
| 10. | At least seven medium-green crystal-vitric lapilli tuffs, each of which is doubly graded. Well-developed banding, consisting of alternating white and green layers, characterizes the upper part of each tuff. Abundant pumice also occurs in the upper part of each deposit. Crystals consist mainly of feldspar and a small amount of quartz. | 150 |
| 11. | Mostly interbedded blue-gray to green silicified claystone, siltstone, and graded lithic sandstones. A few crystal-vitric lapillistones and coarse tuffs also present. The tuffs are several feet thick. The lithic sandstones are mostly less than 1 foot thick. All of the sedimentary deposits are tuffaceous. Some of the sandstones and siltstones in the middle and upper part of the interval are purplish to olive green. A few are distinctly mottled purple and green. Most of the lithic clasts in the graded beds are fine grained to porphyritic and probably basaltic to andesitic. | 249 |
| 12. | Interbedded crystal-vitric lapillistones, lapilli tuffs, bluish-gray silicified siltstones and claystones, and a very few graded lithic sandstones. The predominant lithology is lapilli tuff and lapillistone. The pyroclastic deposits are green to light green and most are doubly graded. Lithic-rich lapilli tuff tends to occur in the lower parts of most pyroclastics; the upper parts are characterized by alternating white and green layers. Crystals consist of plagioclase and a small amount of quartz. | 70 |

*Lower part of Foggy Creek (map unit Pfc)*

| | | |
|---|---|---|
| 13. | Interbedded blue-gray silicified siltstones, claystones, and graded lithic sandstones. The interval also contains a few thin layers of limestones with corals and brachiopods. | 14 |
| 14. | Dacitic crystal-vitric lapillistone; well stratified. The tuff appears to be a fallout deposit. It is characterized by a light-green color and abundant quartz crystals. | 4 |
| 15. | Black to greenish-black limey siltstone-claystone. Deposit is thin to medium bedded. At 15 feet above base of interval, a 2-foot zone of rugose corals is preserved in growth position. | 55 |
| 16. | Dacitic crystal-vitric lapillistone. The lapillistone is poorly exposed but appears to be well stratified and is probably a fallout deposit. The deposit is characterized by a light-green to gray color and abundant quartz crystals, many of which are 2 to 3 mm in diameter. | 12 |

## SECTIONS 22 & 23

Section begins in lowest strata on northeast side of ridge and extends southward along narrow crest of ridge. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Part of Dry Canyon (unit ℙdc)* | | |
| 1. | Several well-stratified tuffs ranging from fine tuffs to medium-grained lapilli tuffs. Mostly vitric and crystal tuffs. Crystals are varying mixtures of quartz and plagioclase. Abundant pumice in parts of these deposits; the pumice is porphyritic with both quartz and feldspar phenocrysts. Upper part of this interval is composed mainly of well-stratified fine tuffs with isolated pumice clasts. This interval probably is the top of the pyroclastic succession described in section 26. This interval includes section 22 and the lower part of section 23. | 800 |
| 2. | Gabbro dike. | 20 |
| *Knife Ridge (map unit ℙkr)* | | |
| 3. | Interbedded limestone, limey siltstone, and green to greenish-yellow fine tuffs, some of which are limey. The deposit also contains a few beds of sandstone composed of volcanic detritus. Most of the sandstones are less than 1 foot thick and are graded. | 100 |
| 4. | Grayish-green coarse crystal tuff, well stratified, composed mainly of plagioclase and quartz; probably dacitic in composition. A distinct decrease in grain size occurs upward in deposit. | 17 |
| 5. | Gabbro dike. | 10 |
| 6. | Covered. | 30 |
| 7. | Interbedded dark-green fine tuffs, medium-grained lithic lapilli tuffs, and graded volcaniclastic breccias. Breccias and lapilli tuffs contain reddish-green and dark-green andesitic clasts. Clast size ranges up to 2 inches in diameter. | 65 |

## SECTION 26

Section begins in the east canyon wall near the top of the steep face. Section is measured down from stratigraphically highest to lowest material.

| Interval | Lithology | Thickness |
|---|---|---|
| *Lower part of Dry Canyon (unit ℙdc)* | | |
| 1. | Grayish-green fine tuffs, dacitic, vitric to crystal composition, well stratified---probably a fall-out deposit. Quartz and plagioclase crystals float in fine tuff matrix. Pumice bears crystals of quartz and plagioclase. | 15 |
| 2. | Gabbro dike. | 75 |
| 3. | Greenish-gray well-stratified coarse tuffs. About 25 percent quartz and plagioclase crystals, 10 percent pumice, and 65 percent fine vitric matrix. Pumice clasts range up to 5 inches long. | |

| | | |
|---|---|---|
| | Pumice bears quartz and plagioclase crystals. Crystals occur in irregular lenses within a vitric matrix. White to yellow banding and mottling present in places. Composition is dacitic. Probably a fallout deposit. | 23 |
| 4. | Greenish-gray well-stratified fine-grained lapillistone. About 20 percent lithic, 20 percent quartz and plagioclase, 30-40 percent pumice, and 20-30 percent vitric matrix. Lithic clasts appear to be mostly fragments of fine tuff. Pumice is dark green and porphyritic; pumice clasts are 5-6 inches long. Deposit appears to be doubly graded. Proportion of lithic material increases at bottom of the interval. | 40 |
| 5. | Porphyritic andesitic intrusive. | 60 |
| 6. | Continuation of interval 5; lithic clasts range up to 9 inches in diameter. This is probably the bottom of interval 5. | 17 |
| 7. | Porphyritic andesite intrusive. | 70 |
| 8. | Grayish-green, very poorly sorted coarse tuff to medium-grained lapilli tuff. Deposit is well-stratified and crystals occur in irregular discontinuous lenses. Lithic, crystal, vitric proportions similar to interval 5. Pumice is highly porphyritic, containing both quartz and plagioclase crystals. Amount and size of lithic clasts increases downward, and tuff is a lithic lapilli tuff at base. Fine-grained and porphyritic andesitic clasts common in lithic part of deposit. Double grading fairly well developed. | 230 |

## SECTION 20

Section begins in lowest strata on north side of the deep gully on the northwest side of Rainbow Ridge. At unit 8, line of section bends into gully and continues up along the bottom of the gully to the top of the ridge. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *West Fork (map unit IPwf)* | | |
| 1. | Mostly a chaotic, massive breccia. Clasts are mostly maroon and slightly porphyritic---probably andesitic. Clasts vary from sand size up to 2-3 inches in diameter. All clasts are angular. Many clasts have altered reddish margins. Parts of the breccia contain crinoid columnals and a few pieces of broken brachiopod shells. Breccias are probably monolithic submarine flow breccias. Interbedded with the breccias are 1- to 3-foot-thick graded sandstone beds composed of material similar to that in the breccias. There is much evidence of penecontemporaneous deformation in the sedimentary deposits. | 382 |
| 2. | Numerous graded calcareous sandstones and fine pebble conglomerates interbedded with reddish siltstones. Graded sediments contain a mixture of volcanic detritus and crinoidal clasts. Color mostly a distinct green to maroon. | 65 |
| 3. | Brownish to greenish-gray graded sandstone interbedded with greenish-gray claystone and tuffaceous siltstone. Some banded intervals are probably stratified fine tuff. Some sandstone beds are slightly limey. Dacitic dike about 20 feet thick in middle of interval. | 75 |
| 4. | Brownish to gray-green graded sandstones and fine pebble conglomerates interbedded with maroon siltstones; a few thin layers of green fine tuff and lapilli tuffs. Clasts in graded beds are heterolithic volcanic material; a few graded beds contain pumice clasts. Interval has a distinct maroon color when seen from a distance. | 237 |
| 5. | Graded sandstones and fine pebble conglomerate interbedded with dense green fine to coarse tuffs. Much contorted stratification. Distinct stratification in the fine to coarse tuffs. Clasts in graded beds are volcanic. | 130 |
| *North Fork (map unit IPnf)* | | |
| 6. | Two olive-green fine- to medium-grained lithic lapilli tuffs. Well-developed internal stratification in both; double grading probably present but not well developed. Fine tuff at the top of each deposit. Both are about the same thickness. | 63 |
| 7. | Light-grayish-green fine-grained crystal lapillistone. Well-developed stratification with layers 2-8 inches thick. Probably a fallout deposit. Crystals consist of plagioclase and a small amount of quartz. | 44 |

| | | |
|---|---|---|
| 8. | Dark-grayish-green fine-grained crystal lapillistone. Well-developed stratification with layers 2-12 inches thick. Pumice clasts abundant, and float in a crystal matrix. Crystals consist of plagioclase and a small amount of quartz. | 44 |
| | End of measured section; remainder of description is for strata overlying interval 8. These strata are exposed on the crest and on the southwest side of Rainbow Ridge down to the first reverse fault (pl. 2). Strata are too badly deformed to measure an accurate section. Strata in this succession consist of dacitic lapillistones and lapilli tuffs interbedded with reworked limey lapillistones, tuffaceous lithic sandstones and pebble conglomerates, and fossiliferous limestones. The most common lithology is lapilli tuff and lapillistone; the fossiliferous limestones are least abundant. The pyroclastics are stratified. Some exhibit good double grading; others are more uniformly stratified and are probably fallout deposits. Most of the lithic sandstones and pebble conglomerates are graded and consist of volcanic debris mixed with varying proportions of fossil material. Volcanic quartz is a common constituent of most of the sandstones and conglomerates. A prominent limestone deposit occurs in about the middle of this succession. This limestone is relatively pure and highly fossiliferous. Fusulinids belonging to the genus *Fusulinella* were collected from this limestone. The limestone can be seen from the Richardson Highway exposed as a series of white triangular-shaped blocks extending across the upper part of Rainbow Ridge at the south end of the ridge and west of section 20. The estimated thickness of these strata is 600 feet, and approximately 60 percent of the strata consist of lapilli tuffs and lapillistones. The lower part of this succession contains the greatest number of potassium-feldspar-bearing pyroclastics found in the map area. | 300 (approx.) |

## SECTIONS 21 AND 21A

Section begins in lowest sedimentary deposits exposed above talus on southwest side of ridge. Section is measured up stratigraphically.

| Interval | Lithology | Thickness |
|---|---|---|
| *Blue Lake unit (map unit IPbl).* (Strata in this unit probably are a facies equivalent of the flows in the lower part of map unit IPwf. Lower part of this unit is faulted out.) | | |
| 1. | Several feet of yellow-green graded sandstones with abundant plagioclase and lesser amounts of green and maroon lithic clasts, overlain by a 6-foot-thick stratified crystal lapillistone containing 10-15 percent quartz and 60-70 percent plagioclase; overlain by a 20-foot-thick white to light-green crystal lapilli tuff, which contains 10-20 percent pumice, 70 percent plagioclase, and 10-15 percent quartz; the lapilli tuff is overlain by several graded sandstones that are calcareous and contain up to 20 percent plagioclase. | 78 |
| 2. | Three green to dark-green lithic lapilli tuffs, with coarse lithic clasts (3-6 inches in diameter) predominant in lower parts; upper parts are mostly crystal lapilli tuffs with plagioclase and quartz. Lithic clasts are green, white, and maroon, and probably andesitic. All three are doubly graded. | 90 |
| 3. | Green to grayish-green calcareous coarse tuffs. Individual layers are graded. Crinoid columnals are abundant. | 16 |
| 4. | Mottled, dark-green and purple sandstones and massive breccias; some graded bedding. | 51 |
| 5. | Dark- to medium-green lithic lapilli tuffs, lapillistones, and fine tuffs. Abundant pumice in parts of these tuffs. Crystals are mostly plagioclase; quartz is present but minor. | 70 |
| 6. | Interval is poorly exposed but appears to consist of calcareous lithic lapilli tuffs, lapillistones, and coarse tuffs. Color varies from light to medium green. Many lithic clasts are white to greenish and fine grained. Several porphyritic andesitic intrusives occur in this interval also. Quartz phenocrysts are not evident in hand specimen. | 578 |
| 7. | Medium-green fine tuffs interbedded with grayish-green graded lithic sandstones. The lithic sandstones are composed of a mixture of volcanic lithic debris and plagioclase. Section 21A (below) probably contains part of the strata faulted out at this point. | 35 |
| | Fault. | |

## SECTION 21A

*North Ridge (map unit ℙnr).* (These strata probably are a facies equivalent of the fine tuffs and graded sandstones in the upper part of map unit ℙwf.)

| Interval | Lithology | Thickness |
|---|---|---|
| 1. | Interbedded fine tuffs, coarse tuffs, and swirly masses of lapilli tuffs; medium to light green. The deposit is well stratified. Large masses of pumice are common and occur scattered randomly throughout the deposit. No quartz observed in hand specimen. | 141 |
| 2. | Light-green doubly graded lapilli tuff. Contains large clasts of pumice in a coarse-to-fine ash matrix. Lithic fragments are rare; the deposit is mostly a crystal-vitric lapilli tuff. | 67 |
| 3. | Medium- to light-green doubly graded lapilli tuff. Lower part contains abundant lithic clasts; the upper part is predominantly composed of crystal and vitric material. Uppermost part is highly pumiceous. The pumice clasts are several inches long and are not compressed into the plane of bedding. No quartz was observed in hand specimen. | 84 |
| 4. | Dark-green doubly graded lapilli tuff. Lower part contains abundant lithic clasts that appear to be fragments of ash and porphyritic andesite with a distinct maroon color. No quartz was observed in hand specimen. | 137 |
| 5. | Medium-green doubly graded lapilli tuff. Lower part contains abundant lithic clasts that consist mainly of maroon scoriaceous fragments and green porphyritic andesite. | 90 |
| | Fault. | |

## SECTION 21 *(cont.)*

| Interval | Lithology | Thickness |
|---|---|---|
| 8. | Crystal-vitric lapilli tuff without stratification; mostly light to medium green. Lithic clasts that appear to be fragments of fine tuff are abundant throughout the deposit. | 15 |
| 9. | Medium- to light-green well-stratified fine tuff. In many places, thin white layers of fine tuff are interbedded with the green tuff. | 406 |
| 10. | Highly contorted fine tuff. The color varies from green to mottled green and white to reddish. Abundant evidence of soft-sediment deformation. The entire deposit appears to have slumped. | 137 |

## SECTION 25

Section begins in the lowest exposed strata at the north end of the ridge. Section is measured up stratigraphically.

*Upper part of North Ridge (map unit ℙnr).* (These strata probably are a facies equivalent of the interbedded fine tuffs and graded sandstones in the upper part of map unit ℙwf.)

| Interval | Lithology | Thickness |
|---|---|---|
| 1. | Light-green to greenish-white fine tuff with highly contorted bedding produced by soft sediment deformation. Very few crystals were observed in the deposit; the composition is mainly vitric. The strata in this interval probably are the same as interval 10 in section 21. | 80 |
| 2. | Interbedded green to light-green fine tuffs, lapillistones, and lapilli tuffs. Some double grading is evident in a few of the deposits. All of the pyroclastics are well stratified. Pumice is abundant in most parts of the deposits and usually is flattened in the plane of bedding. Quartz is rare or absent in the pyroclastics. Most of the deposits are crystal vitric. | 185 |
| 3. | Several green to dark-green lithic lapilli tuffs. All are characterized by highly contorted stratification, probably resulting from soft-sediment deformation. The lithic clasts consist mostly of light- to medium-green fine tuff and green porphyritic andesite. A few of the porphyritic clasts contain a minor amount of quartz. | 310 |
| 4. | Interbedded calcareous siltstones and graded calcareous lithic sandstones. Color varies from green to greenish brown. Carbonate fragments are mostly crinoid columnals; lithic debris is entirely volcanic. | |
| 5. | Several green to dark-green lithic lapilli tuffs with contorted stratification similar to deposits in | 45 |

interval 2. A few of the deposits are graded tuffaceous sandstones, and many of these exhibit contorted stratification. A few of the deposits are calcareous. Some clasts of pumice are present in parts of these deposits. 365

## SECTION 27

Section begins at the lowest exposed strata near the floor of the canyon. The section is measured up stratigraphically. These strata are probably a facies equivalent of part of the Dry Canyon unit (unit ℙdc).

| Interval | Lithology | Thickness |
|---|---|---|
| *Eagle Ridge (map unit ℙer)* | | |
| 1. | Pyroclastic(?) breccia, dark green to dark greenish brown. The bedding usually is massive and not distinct. The breccia consists mainly of dark-green clasts with distinct white plagioclase phenocrysts, giving the clasts a characteristic speckled appearance. Other clasts are white to light-green fine tuff, and light-colored clasts containing quartz and plagioclase phenocrysts. | 133 |
| 2. | Calcareous green to brownish-green lithic sandstones and conglomerates interbedded with medium- to dark-green fine tuff. The sedimentary deposits are graded and the fossil debris is mostly crinoid columnals. The amount of fine tuff increases upsection. Most of the sediments are tuffaceous. The sediments are composed mostly of lithic volcanic debris and plagioclase. | 46 |
| 3. | White to greenish-white well-stratified fine tuff. Thickness varies abruptly along strike. | 7 |
| 4. | Essentially the same as the strata in interval 2. | 37 |
| 5. | Very dark-green to dark-greenish-black lithic sandstones. Graded bedding is common in most of the sedimentary deposits. The sandstones are composed of volcanically derived lithic grains and plagioclase. Most of the deposits appear to be tuffaceous. A few thin beds of green fine tuff are interbedded with the graded sediments. | 82 |

# APPENDIX II - UNMEASURED STRATIGRAPHIC UNITS

The descriptions in this appendix are for those map units for which no measured section was made due to poor exposures or complex structure. The descriptions are based on observations of several outcrops that are representative of the map units.

## WEST GULKANA (map unit ℙwg)

This unit consists entirely of green to grayish-green massive basaltic to andesitic amygdaloidal flows. Bedding is apparent only from a distance, and the bedding planes are probably boundaries between individual flows. The flows are massive in places and brecciated in others. No clear indications of flow tops or pillows were seen. Most of the flows are porphyritic with plagioclase and mafic (amphibole and pyroxene) phenocrysts. Amygdules are filled with chlorite, quartz, chalcedony, and a minor amount of epidote.

## SOUTH CIRQUE (map unit ℙsc)

This unit is best exposed on the south side of the central part of Rainbow Ridge (pl. 2). Three principal lithologies occur within this unit. These are, in order of their abundance: (1) andesitic and dacitic crystal-vitric to lithic pyroclastics, (2) tuffaceous lithic sandstones and conglomerates, and (3) impure to pure fossiliferous limestones. The pyroclastics contain abundant plagioclase, some of which has been replaced by epidote, giving the deposits a distinct yellow color. Pumice is present in all of the pyroclastics and typically is flattened in the plane of bedding. Some of the lithic-rich pyroclastics contain distinctive maroon lithic clasts of basalt or andesite. Nearly all of the pyroclastics are well stratified. The tuffaceous sediments contain lithic clasts of volcanic origin and abundant plagioclase, which is typically replaced by epidote. The amount of plagioclase in these sediments seems to be somewhat greater than in the rest of the Tetelna Complex. Detrital quartz, probably of volcanic origin, is also an important component of the sediments. Most of the limestones contain plagioclase, quartz, and lithic impurities that probably were derived from pyroclastic materials. Crinoidal columnals are the most common fossil fragments, but pieces of brachiopod, bryozoan, and coral skeletons are present also. Very rapid lateral changes from one lithology to another are typical of this unit.

## RICHARDSON HIGHWAY (map unit ℙrh)

This unit can be seen in several exposures along the Richardson Highway and at the south end of Rainbow Mountain (pl. 2). Strata in this unit are predominantly crystal-vitric lapillistones and lapilli tuffs of dacitic composition. Fine tuffs and a few lithic lapilli tuffs also occur scattered throughout the unit. However, the fine tuffs tend to be most abundant in the upper part of the deposit. A few thin intervals (40 to 100 feet thick) of sedimentary rocks also occur, but their stratigraphic position is not established. These sediments are mostly black argillaceous siltstone and black claystone interbedded with a few brown-weathering, slightly calcareous lithic sandstones. Most of these sandstones are graded. A few thin limestone beds composed largely of sand-sized skeletal debris are exposed west of Phelan Creek along the west bank of the creek. No fossils were found in the limestones. The pyroclastics are well stratified and contain abundant pumice, most of which is flattened in the plane of bedding. The pumice is porphyritic and contains abundant phenocrysts of quartz and plagioclase.

## CAMP CREEK (map unit ℙc)

The best exposures of this unit occur at the south end of Rainbow Mountain (pl. 2). This unit consists of interbedded green to dark-green coarse to fine tuffs, thin white fine tuffs, a few lapilli tuffs, graded lithic sandstones and conglomerates, and a few thin layers of calcilutite and graded calcarenite. The pyroclastics typically contain dark-green, mostly nonporphyritic pumice clasts. Lithic fragments and plagioclase crystals are also present in many of the lapilli tuffs and coarse tuffs. The graded sediments are partly tuffaceous and consist of lithic volcanically derived fragments and plagioclase. No fossils were recovered from the limestones. Most of the pyroclastics appear to be andesitic.