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THE DENALI FAULT (HINES CREEK STRAND) IN NORTHEASTERN MT. MCKINLEY NATIONAL PARK, ALASKA

by

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ABSTRACT

The Hines Creek fault, the northern strand of the Denali fault system, is located on the northern flank of the central Alaska Range. An area of approximately 250 square miles in northeastern Mount McKinley National Park, on either side of the trace of this fault, was mapped geologically.

The Hines Creek strand separates Precambrian (?) Birch Creek Schist on the north from Tertiary and Paleozoic (?) rocks on the south. The fault trace could only be approximately located because of cover, but it displays a large southward bend in the western part of the area.

Folds and minor structures in the Birch Creek Schist, Paleozoic (?) slate, Paleocene Cantwell Formation and younger Tertiary units all trend approximately N 80°E, parallelling the average strike of the range. Intensity of folding increases with age, suggesting several recurrent episodes of approximately north-south compression through Miocene time.

To be compatible mechanically with this stress field, the Hines Creek fault probably functioned as a thrust or reverse fault with the north side upthrown. Evidence of strike-slip faulting was not found, and Holocene deposits are undisturbed by the fault. Microseismic work, however, suggests that the Hines Creek strand is still active.

APPROVED:

Campbell Craddock
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June 2, 1972

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INTRODUCTION

Intent

Synthesis and analysis must proceed with equal vigor if the course of scientific investigation is to progress efficiently. Too much of one produces false associations and overly speculative results, while an excess of the other leads to an unwieldy, suffocating mass of random data. By this token, it is fitting that, in this time of global theories interpreting and reinterpreting structural features rimming the Pacific, particularly the Denali fault, analytical studies be undertaken on a more modest scale to fill in the gaps in our knowledge. Only when precise data on many small areas are assembled can a global synthetic hypothesis become more than a calculated speculation.

Nature of the problem

Since its recognition as a major fault zone (St. Amand, 1954, 1957; Sainsbury and Twenhofel, 1954), the Denali fault has received considerable attention by earth scientists. Its location on the Pacific rim as well as its lengthy trace make it an important structure for geotectonic theorists. Unlike some of the other major circum-Pacific faults, however, detailed geologic information about the Denali fault system is generally lacking.

There are almost as many theories concerning the origin and mechanics of this fault as there are theorists. The principal ideas are summarized below.

1) Some global geophysicists cite the Denali, like the San Andreas, as a transform fault (Tobin and Sykes, 1966, 1968; Richter and Matson, 1971). Earthquake studies (Stauder, 1968) indicate the Pacific plate is moving northwestward under the Aleutian arc; this is consistent with an active transform Denali fault.

2) By analogy with other large faults which parallel the Pacific margin, the Denali fault has been explained as primarily a dextral strike-slip feature. Proponents differ on the amount of slip. St. Amand (1957) favored >150 miles of net slip; Cady and others (1955) cite 100 km of right-lateral slip; Grantz (1966) is undecided as to the exact amount, and Wahrhaftig (in Grantz, 1966) suggests that strike-slip movement has been quite limited. Similar disagreements arise concerning timing of the inception of transcurrent movement on the Denali fault.

A variation of the strike-slip mechanism is the bent strike-slip concept championed by Carey (1959). He outlines a bending of the fault around a hinge at its northernmost point as the Arctic and Atlantic basins opened. Churkin (1969, 1970) bends the Alaskan structures by Pacific sea-floor spreading while Grantz (1966) suggests that a collision of North America and Asia is responsible for the present curved trace of an originally straighter fault.

3) Other workers postulate a reverse fault. Richter and Jones (1970) sketch a history with the Denali fault acting as a subduction zone in the early Mesozoic. A change in direction of spreading in the Pliocene reactivated this fossil Benioff zone as a dextral trans-

form fault, accounting for recent horizontal movement.

Each of these theories is reasonable, but without additional facts, there is no way to decide among them. One point becomes obvious: the actual history of the Denali fault system is probably quite complex in order to lead so many competent workers to such contradictory conclusions.

Scope of study

At its northernmost point, which is also the point of maximum curvature, the Denali fault consists of two strands, the McKinley strand to the south and the Hines Creek strand to the north. The eastern bifurcation occurs near the Delta River; the two strands coalesce again west of Mt. McKinley. This study is concerned with the Hines Creek strand, the more highly curved and probably older strand.

Located about 18 miles north of the more seismically active McKinley strand, the Hines Creek strand is only discontinuously expressed by distinctive topographic features. The McKinley strand, with its shorter trace and better topographic expression, is cited as a more mechanically efficient "short circuit" (Grantz, 1966) of the older Hines Creek strand. The older trace is a more fundamental geologic break, however, separating older schists on the north from younger sedimentary rocks on the south. If the Denali fault system has a complex history, possibly with more than one type of movement, there is no better place to study this earlier history than on the older Hines Creek strand, where there is less evidence of recent activity. Also, this strand is situated on the hinge of Carey's (1959) oroclinal bending. A more promising area for definitive detailed geologic work on the fault system would be difficult to find.

The questions upon which this study is focused include:

1) Where is the Hines Creek fault trace, and exactly how straight and continuous is it? Is it a unique trace, a zone, or several parallel faults?

2) What is the mechanical classification (reverse, thrust, normal, or strike-slip) of the Hines Creek fault? Has this classification changed through time?

3) Through what periods of geologic time was the fault active, and is it still active?

4) How much slip has occurred along the fault?

5) How does the movement picture of the Hines Creek fault relate to the Denali fault system as a whole?

Description of area

Situated on the northern flank of the central Alaska Range, the study area comprises about 230 square miles in northeastern Mount McKinley National Park (see Figure 1). It extends roughly 6 miles on each side of the park road from mile 6.8 to mile 33.3. Including parts of the Healy C-5, C-6, D-5, and D-6 quadrangles, the study area is centered approximately at 149°30'W longitude, 63°42'N latitude.

The most striking physiographic feature of the area is a broad linear lowland which bisects the study area from east to west and contains the trace of the Hines Creek fault. This rolling lowland is

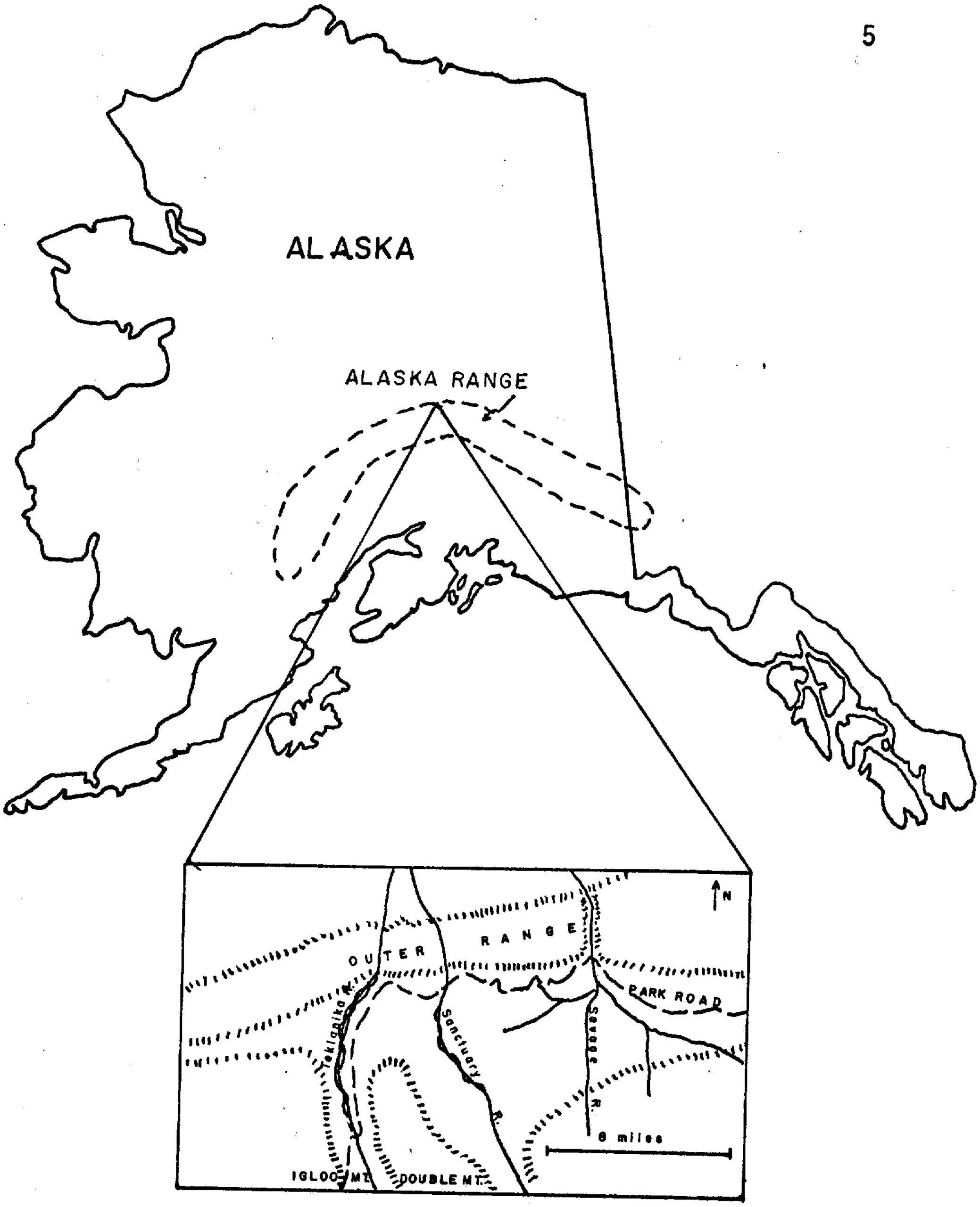

Figure 1. LOCATION OF STUDY AREA.

bounded on the north by the slightly arcuate foothills of the Alaska Range, known as the Outer Range. Many of these deeply weathered peaks possess flat tops, possibly due to the exhuming of an older erosion surface. Within the area, the foothills are cut by three major northward-flowing rivers, the Savage, Sanctuary, and Teklanika. The source for these rivers lies south of the central lowland in the Alaska Range proper. These more rugged peaks form the southern boundary of the study area.

Procedures

The primary objective of study was to develop a detailed geologic map along a segment of the fault. This mapping was done during July and August, 1971, on 1:40,000 aerial photos; detail was later transferred to 1:63,360 U.S. Geological Survey topographic quadrangle maps. I was ably assisted in the field by a variety of geologists and associates including Bob Hickman, Tom Bultman, Dr. Walter Zürn, Professor Campbell Craddock and John Craddock. Due to time, terrain, and weather limitations, much of the mapping was necessarily of a reconnaissance nature.

In addition to basic field mapping, special attention was paid to mesoscopic structures in the various rock units as records of strain during deformation. For unconsolidated deposits, both physiography and air photo interpretation were used to gain insight into the structure and especially the folds near the fault.

The field studies were followed by petrographic microscope analysis as well as radiometric age-dating and chemical analysis of carefully selected specimens. Some plant fossil material was sent to the U.S.

Geological Survey in Menlo Park, but none of the fossils was well enough preserved for identification at the generic level.

Acknowledgements

The days of the lone-wolf geologist are over; without the contributions of many people, I could not have begun to undertake this project, much less complete it. All inaccuracies and errors, however, I claim as my own.

The financial backing for this project was provided by a National Science Foundation research grant to Professor Craddock. In addition, I was assisted by an N.S.F. fellowship for the summer as well as for the 1971-72 academic year.

While in the field, members of our party, Professor Craddock, Bob Hickman, Tom Bultman, and Tom DeKeyser, gave not only helpful consultation on geologic problems but provided ample moral support throughout the long season. Dr. Walter Zürn and John Craddock aided me in field mapping during their brief stays. The National Park Service was helpful in many ways, permitting specimen collecting within the park and generously offering us the use of the Savage River ranger cabin for one of our mapping forays. Bob Jenkins and Mike Brauner offered their time and expertise in the bulk chemical analysis of certain specimens. The troublesome task of seeing this manuscript into print was handled expertly by Judy Welch.

Additional thanks must go to the people who introduced me to the Alaska Range, Professor Campbell Craddock and Bob Hickman. Bob's pre-

cise mapping techniques and general enthusiasm in the field supplied a model well worth emulation. Finally I am grateful to Professor Campbell Craddock, who conceived this project and helped me see it to completion. His advice and criticism have proved exceedingly valuable, not only during this study, but throughout my career at the University of Wisconsin.

REGIONAL GEOLOGY

Structure

Stretching across southern Alaska for approximately 600 miles is an arcuate mountain belt known as the Alaska Range. Commonly 30-40 miles wide, this mountain barrier is classified physiographically as a part of the Pacific Mountain System (Wahrhaftig, 1965). Although the structural pattern is complicated by refolding, faulting, and unconformities, the structural elements of the Alaska Range, both folds and faults, display a striking degree of parallelism. Just as the axis of the range bends around, paralleling the Pacific Coast, so do the outcrop belts and fault traces of the Alaska Range. This concordance of structural and physiographic trends is the most striking feature of this region.

Folds occur on many scales in the Alaska Range. The range itself is grossly synclinal, with Paleozoic and Mesozoic units cropping out in belts parallel to the range axis (Reed and Lanphere, 1961). Just as the pre-Tertiary rocks are synclinal, the Paleocene Cantwell Formation in its type area forms a west-trending synclinorium (Wolfe and Wahrhaftig, 1970). Intensity of folding differs markedly among the various units. For structural considerations, rocks of the central Alaska Range can be grouped into four units:

1) Crystalline schists, such as the Birch Creek Schist, are the most intensely deformed; these rocks have good schistosity and have been compressed so that the axial planes of their closely spaced folds are nearly horizontal.

2) Sedimentary and volcanic rocks of Paleozoic and Mesozoic age display some open folds, but these beds are more commonly isoclinally folded with subvertical axial planes.

3) The Cantwell Formation is thrown into large open folds but is vertical locally.

4) Even the unconsolidated Tertiary deposits have not escaped deformation. Dips up to 50° are common in broad open folds. Intensity of folding decreases with age, but all Tertiary units are involved to some degree. This suggests that the Alaska Range has been a zone of active deformation throughout much of Phanerozoic time; each of several compressive episodes left its record there.

Faults parallel to the range axis give additional testimony that the Alaska Range is indeed a locus for deformation. Most of the faults in Alaska thought to be strike-slip lie in central and southern Alaska. They, too, parallel the Pacific margin; several coalesce in southeastern Alaska to preserve this relationship. Southward from the Alaska Range, the inferred nature of faulting changes toward the coast from strike-slip to northward-dipping thrusts.

The major fault system of central Alaska, the Denali fault, stretches northeastward from Bristol Bay, eastward through the Alaska Range and finally southeastward to Chatham Strait. In its 1300-mile course, it occupies a marked physiographic low for much of the distance. Although the mechanical nature of the McKinley and Hines Creek strands is in dispute, strike-slip movement has been claimed for much of the rest of its length. Grantz (1966) emphasizes the strike-slip nature of this fault and others, but there is evidence of associated thrusting. The Holitna fault, one of

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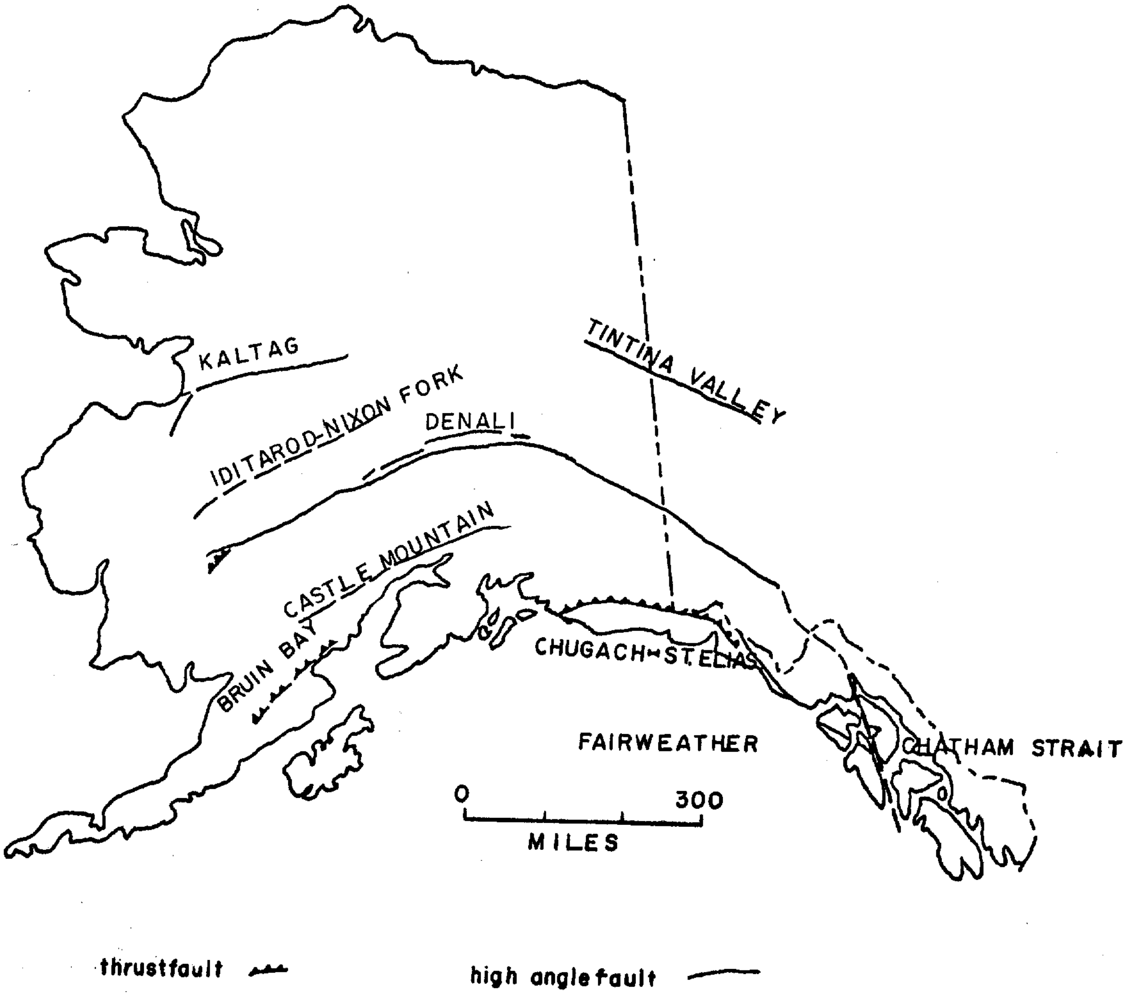
Several other lineaments in central Alaska, both to the north and south of the Alaska Range, have been cited as right-lateral strike-slip features (Grantz, 1966). This mode of deformation can be considered characteristic of the central Alaska region at the present time (see Figure 2).

Stratigraphy

As mentioned in the previous section, the Alaska Range is the site of a zone of crustal mobility; it has been the locus of mountain-building episodes dating back as far as middle Paleozoic time (Moffit, 1954). Numerous unconformities indicate repeated cycles of uplift and erosion. The present Alaska Range, a Cenozoic feature, is but the latest in a succession of mountains which have risen here.

The oldest formation in the Alaska Range, the Birch Creek Schist, is a quartz-sericite schist with minor interbedded marble. Making up the Outer Range, this formation represents metamorphosed sandstones and other mainly siliceous sedimentary rocks. Although some workers have designated this unit as early Precambrian in age (Mertie, 1937), no proof of age exists (Wahrhaftig, 1968). Rb-Sr studies have yielded ages of 120 - 1,170 million years for the Birch Creek Schist (Wasserburg and others, 1963), but these results are compatible with Mesozoic metamorphism in the light of recent strontium remobilization work (Lanphere, in Wahrhaftig, 1968). Due to these vagaries, the time age of this formation remains in doubt, but it has been assigned to Precambrian or lower Paleozoic (Péwé and others, 1966).



AFTER GATES & GRYC, 1963

Figure 2. MAJOR FAULTS OF ALASKA

The lower Paleozoic record is only slightly less obscure. Southern Alaska lay then in the eugeosynclinal tract of the Cordilleran geosyncline. Graywacke, argillite, shale, chert and conglomerate were the dominant detrital rock types, but periodic quiescence allowed the formation of thick limestones at some places during every period of the Paleozoic era (Gates and Gryc, 1963). Volcanism was prominent, especially during the Mississippian, Permian, and Triassic periods. Basaltic and andesitic flows, tuffs, and breccias converted most of Alaska south of the Yukon River into a submarine volcanic field during these last two periods (Wahrhaftig, 1965). Emergent episodes complicate reconstruction of the Paleozoic history by having allowed many of the rocks to be destroyed by erosion. Unconformities suggest emergence during the Pennsylvanian and probably during the first pulses of orogeny in the late Silurian or early Devonian since no rocks corresponding to these time intervals are found in all of Alaska.

The Paleozoic uplifts foreshadowed events of the middle and late Mesozoic when the Alaskan mobile belt was differentiated into seven west-trending geosynclines with corresponding positive areas (Gates and Gryc, 1963). Intrusion of granitic plutons accompanied this orogenic activity. Poorly sorted detritus filled the Alaska Range geosyncline until middle Early Cretaceous. At this time, widespread orogeny affected the whole Alaskan eugeosyncline; no rocks of Aptian age are found anywhere in Alaska. For the Alaska Range, this uplift and folding marked the end of marine deposition.

Tertiary time began with uplift and deformation creating the ancestral Alaska Range. This diastrophism took a different form in the nearby Wrangell Mountains to the south as piles of lavas and tuff beds built those peaks. Subsequent to this orogeny, Paleocene subsidence along the axis of the present Alaska Range formed a continental basin; deposition of sandstone, conglomerate, and coal, plus some extrusive volcanism produced the 10,000 feet of the Cantwell Formation. These continental sedimentary and volcanic strata were then folded, metamorphosed slightly, and intruded with structurally diverse sills, dikes, and other plutons. Erosion reduced the range to a series of depositional basins once again in the Oligocene and Miocene; during this time fine sands and coals of the coal-bearing group were laid down on this lowland (Wahrhaftig, 1970a).

The present Alaska Range began to rise in the Pliocene. Orogeny, expressed through folding and faulting, began in the south and spread northward (Wahrhaftig, 1970c). The Pliocene (?) Nenana Gravel, accumulating to the north as a bajada, was ultimately involved in this orogeny and folded. Pleistocene deposits from the four glaciations recognized in central Alaska are not deformed, suggesting that this most recent orogeny ended before 3 million years ago. Broad upwarping with some faulting along the McKinley strand of the Denali system has been the characteristic tectonic mode since that time.

ROCK UNITS

The rock units of northeastern Mount McKinley National Park are difficult to divide into the simple categories of igneous, metamorphic, and sedimentary rocks. Most of the units are metamorphosed to varying degrees, and one sedimentary formation has interbedded pyroclastics and flows. In an attempt to deal with these complications, the following basis for classification will be used.

Metamorphic rocks include those rocks which have been deformed so greatly that stratigraphic sequence and thickness are difficult, if not impossible, to determine. The Birch Creek Schist and the pre-Cantwell metasedimentary rocks fall in this category. Sedimentary rocks include the Cantwell Formation's volcanic upper part since these rocks have been previously grouped together. Other sedimentary units are the Tertiary coal-bearing group, the Nenana Gravel, and Quaternary sediments. Igneous rocks consist of intrusive bodies--dikes, plugs, and other plutons--which invade other units.

In descriptions of these rocks, color terminology follows the Geological Society of America Rock Color Chart and grain size terms are from the Wentworth Scale. Bedding thickness descriptions are as follows:

>10 feet	massive	2-6 inches	thin-bedded
5-10 feet	very thick-bedded	1/4-2 inches	very thin-bedded
2-5 feet	thick-bedded	<1/4 inch	laminated
6-24 inches	medium-bedded		

The description and classification of igneous rocks is after Williams, Turner, and Gilbert (1954).

METAMORPHIC ROCKS

Precambrian (?) Birch Creek Schist (p€bc), quartz sericite schist with quartzite, phyllite and marble.

The northern foothills of the Alaska Range extend in a slightly arcuate belt about 3 miles wide across the entire area; these low flat-topped mountains are composed almost entirely of Birch Creek Schist. In fact, the trend of the Outer Range follows closely the strike of the foliation in the schist. It is the only bedrock unit that crops out north of the Hines Creek fault; nowhere in Alaska is it found south of the Denali fault. The steeply dipping foliation makes the schist very susceptible to mechanical weathering, and it is extensively buried in its own debris. River valleys provide many of the best exposures of this unit.

Cited by early workers as the oldest unit in Alaska, the Birch Creek Schist is also one of the hardest to divide stratigraphically. No attempt was made in this study to measure its thickness; Wahrhaftig (1968) suggests 10,000 feet as a tentative minimum. His estimate was measured perpendicular to axial plane cleavage in minor folds and is not represented as a true stratigraphic thickness. The Birch Creek Schist is in tectonic contact with a variety of units across the Hines Creek fault but in the study area is seen in depositional contact only with the Tertiary units. On the northern flanks of the foothills, the Tertiary coal-bearing group and the Nenana Gravel can be seen unconformably overlying this unit. Basaltic dikes up to 20 feet wide also cut the Birch Creek Schist in the extreme northwestern part of the area.

Three lithologic types characterize this unit, with many gradations among them. Medium dark-gray quartz-sericite schist is the most common rock type in the McKinley Park area. Although very thick bedding is common in this quartz-rich variety, laminated beds are also seen. Grain size is highly variable, from fine- to very coarse-grained. A typical unit is 70-90 percent quartz with 5-20 percent sericite and 5-10 percent calcite. Mortar structure, strained extinction and elongate quartz grains result from prolonged deformation. Black or dusky yellowish green phyllite, the second major type, is invariably laminated and fine-grained. This rock type contains considerably more sericite, chlorite, and graphite, the three together varying up to 20 percent; quartz content is quite high, rarely less than 40 percent. The third and least common rock type is brownish-gray marble, fine-grained and thin-bedded. Angular, recrystallized calcite grains up to 1/2-inch make up 70 percent of these marble lenses, the remainder being subangular quartz grains. The quartz sericite schist and the phyllite combine in almost all proportions; some calcite is present in nearly all rocks.

The metamorphic grade of the Birch Creek Schist is established as greenschist facies by a few layers of epidote-chlorite-albite schist on the southwest flank of Mount Wright, one mile northwest of Sanctuary River campground. Overall color is medium dark gray weathered and dusky yellowish green to medium light gray fresh; phyllitic portions display browns, greens, reds and yellows. Outcrops containing abundant pyrite cubes are characteristically moderate reddish brown; locally prominent concordant white quartz veins up to 20" wide serve to lighten the overall aspect of the schist.

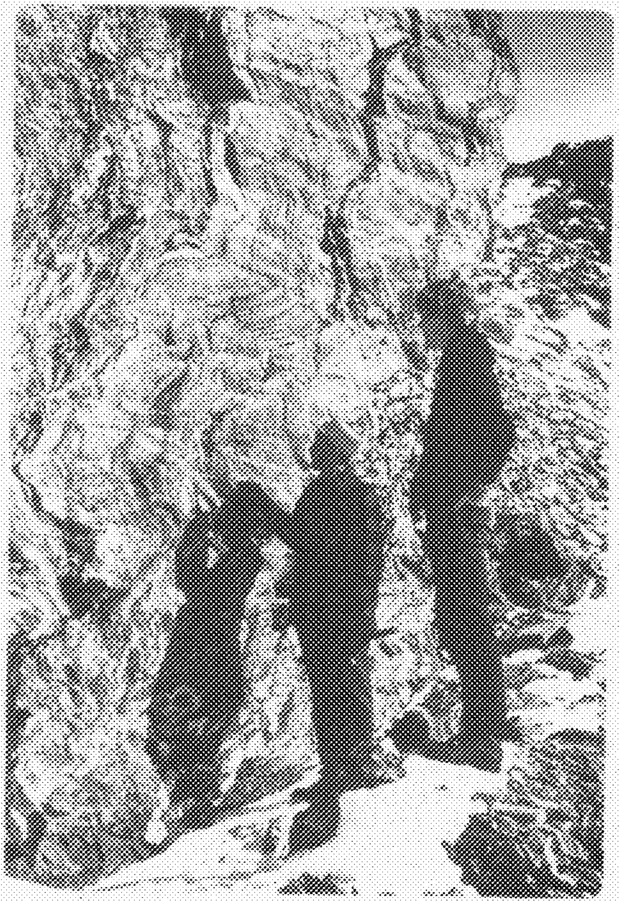
Mesoscopic and microscopic structures are the most conspicuous features of the Birch Creek Schist, however (see Figure 3). The primary foliation, S_1, is folded tightly on scales ranging from tiny crinkles to folds with amplitudes and wave lengths of several feet. A persistent fracture cleavage, S_2, in roughly an axial plane position with respect to the folds, cuts S_1. In addition to these mesoscopic features, microscopic kinking, boudinage, and cataclastic augen structure are prominent in this unit.

There is good reason to suppose that S_1, the primary foliation, parallels the original bedding in the Birch Creek Schist. The gross lithologic layering of quartzite and phyllite parallels this foliation; metamorphic differentiation is a dubious but possible explanation on this scale. Color banding in phyllite layers, quite complex and with considerable lateral continuity, is more difficult to explain; any differentiation process would have to be quite selective. Most definitive, however, are the marble lenses which also parallel the foliation. These lenses are very scarce even though calcite is a common constituent of these rocks, so differentiation by heat and pressure cannot be used to explain them. These marble beds represent original bedding; their concordance with the primary foliation proves S_1 is a bedding plane foliation in this area.

The age of the Birch Creek Schist is difficult to determine. The original marine shales and siliceous sediments, together with minor sills or volcanic rocks, have been altered by metamorphism so extensively

Figure 3. Steeply dipping Birch Creek Schist (p€bc) in extreme northeastern part of area. Note the tight folds and nearly horizontal axial planes which parallel S_2.

View is to the east in SE/4 SE/4 NW/4 Sec. 31, T. 13 S., R. 9 W. of Healy C-5 quadrangle.



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that no fossils or original textures exist. Rb-Sr ages from 120 - 1,170 million years have been obtained for this unit (Wasserburg and others, 1963), but these may result from only the most recent time of metamorphism. Lanphere (in Wahrhaftig, 1968) believes that these isotopic data are compatible with Mesozoic metamorphism. Thus, no isotopic work to date proves the original early Precambrian age designation (Mertie, 1937). These problems have led to the assignment of the Birch Creek Schist to the Precambrian or lower Paleozoic (Péwé and others, 1966).

Paleozoic (?) (Pz), slate, sandstone, chert, limestone, conglomerate, and phyllite.

The oldest unit south of the Hines Creek fault is a sequence of tightly-folded metasedimentary rocks, most of which display foliation. Dominantly slate, these rocks crop out extensively in the southeast corner of the study area as well as forming a broad west-trending belt approximately between Teklanika campground and the Teklanika River bridge. Due to its thin bedding and pronounced foliation, this unit is not very resistant to erosion and forms low rounded hills, except where intruded by igneous bodies or capped by more resistant overlying units. Outcrops are highly fractured by frost action and are commonly slumped out of place.

Due to the intense folding of these metasedimentary rocks, thickness estimates are difficult to make. The outcrop belt crossing the Teklanika River is 3 miles wide, and the topographic relief is 2500 feet. It is difficult to account for such an extensive outcrop, even with that no fossils or original textures exist. Rb-Sr ages from 120 - 1,170 million years have been obtained for this unit (Wasserburg and others, 1963), but these may result from only the most recent time of metamorphism. Lanphere (in Wahrhaftig, 1968) believes that these isotopic data are compatible with Mesozoic metamorphism. Thus, no isotopic work to date proves the original early Precambrian age designation (Mertie, 1937). These problems have led to the assignment of the Birch Creek Schist to the Precambrian or lower Paleozoic (Péwé and others, 1966).

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Laminated, medium light gray slate is the dominant rock type in this sequence (see Figure 4). A typical slate is composed of 15-50 percent muscovite, 40-70 percent quartz, 5-10 percent opaque hematite or carbonaceous material, and a trace of plagioclase. These fine-grained, foliated rocks are commonly interbedded with fine-grained, dirty sandstone, rust-stained and cut by 1/2-inch quartz veins. Sandstones are light gray and very fine-grained; cross-bedding in 2-inch sets is locally present. The third most common rock type is medium light gray, fine-grained, laminated limestone. Extensively recrystallized, these limestones are cut by 1/4-inch veins of coarse, crystalline calcite. Primary features preserved include laminae, cross-bedding, and penecontemporaneous folds; no fossils were found in these metamorphosed limestones. Banded cherts and grayish green phyllites occur extensively; these rock types are found associated in many places. Poorly sorted conglomerates, with 1-inch subangular clasts of quartzite, igneous rock, and sandstone, complete the assemblage of rocks comprising the metasedimentary sequence.

The intense isoclinal folding of these rocks is the primary reason they have been grouped together; in the face of such structural com-

Figure 4. Small, tight syncline in bedding of black argillite of Paleozoic (?) age located 3.5 miles south of mile 8.5 on the park road in the southeast corner of the study area.

View is to the southeast in SW/4 SW/4 NW/4 Sec. 32, T. 14 S., R. 9 W. in Healy C-5 quadrangle.

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View is to the southeast in SW/4 SW/4 NW/4 Sec. 32, T. 14 S., R. 9 W. in Healy C-5 quadrangle.

plexity, further stratigraphic subdivision must await more detailed study. Folding is present on all scales from microscopic crinkles in the slates to tight, isoclinal folding of the beds themselves. In addition, all rock types display bedding plane foliation in some outcrops; the slates are locally cut by kink bands and slip cleavage.

The sedimentary features preserved indicate deposition in a marine basin mainly below wave base. The fine laminations present in the majority of the rocks are one result of this environment of formation; the fine grain size, even after coarsening due to metamorphic recrystallization, is another. Angularity and poor sorting of the original sediments suggests that deposition was rapid at times and in a low-energy environment. The marine basin was probably fed by an adjacent high nearby, although no definitive evidence for a particular source area was found. Clasts from conglomerate lenses are mainly sedimentary rocks of this sequence and igneous rocks; no clasts could be positively identified as Birch Creek Schist. The presence of argillite ripups indicates some episodes of high energy interrupted the quiet deposition.

Due to lack of fossils, the age of the metasedimentary sequence can not be established precisely. Capps (1931) dated the outcrop belt across the Teklanika River as Paleozoic, but he assigned the slates and associated rocks in the extreme southeastern part of the study area to the Jurassic. Two plutons which cut this sequence have been dated radiometrically; UW 1562/1 from the eastern area yielded a 359 ± 44 million year age, while UW 1562/2 from the Teklanika River outcrop belt yielded 329 ± 30 million years. On this basis, neither sequence is probably any younger than middle Paleozoic.

SEDIMENTARY ROCKS

Paleocene Cantwell Formation (Tc/Tv), conglomerate, sandstone, argillite, and volcanic rocks.

The rugged mountains of the central Alaska Range are fashioned mainly from a thick, continental conglomerate, the Cantwell Formation. In the study area, this formation forms rugged hoodoos (see Figure 5) near the head of Jenny Creek on the eastern margin and the jutting peaks of Double Mountain and Igloo Mountain in the southwest corner. This massive unit serves as a caprock on some ridges, protecting the weaker, less competent units from erosive agents.

The bedding style of this unit is massive, in marked contrast with other units in the area. Beds tens of feet thick are common in the conglomerates of the Cantwell Formation. The subordinate sandstones are medium- to thin-bedded, and the argillite is usually laminated. In the type area, the east wall of the Nenana River canyon from the mouth of Slime Creek northward for about 7 or 8 miles in the Healy C-4 quadrangle, this formation attains a maximum thickness of about 10,000 feet (Wolfe and Wahrhaftig, 1970). In the study area, erosion or non-deposition has reduced this amount, the maximum thickness being approximately 2000 feet of volcanic rocks, overlying approximately 3000 feet of sedimentary rocks at Double Mountain.

The Cantwell Formation is bounded above and below by angular unconformities. This unit overlies the Paleozoic metasedimentary rocks upon a strikingly folded angular unconformity. The Cantwell Formation is, in turn, overlain unconformably by the Tertiary coal-bearing group.

Figure 5. Paleocene Cantwell Formation (Tc) forms hoodoos in southeast corner of area about 2.5 miles south of mile 8.0 on the park road in SW/4 NW/4 NE/4 Sec. 29, T. 14 S., R. 8 W in the Healy C-5 quadrangle.

View to the north reveals light ridges of Cantwell Formation with the Birch Creek Schist of the Outer Range visible at the top of the picture.

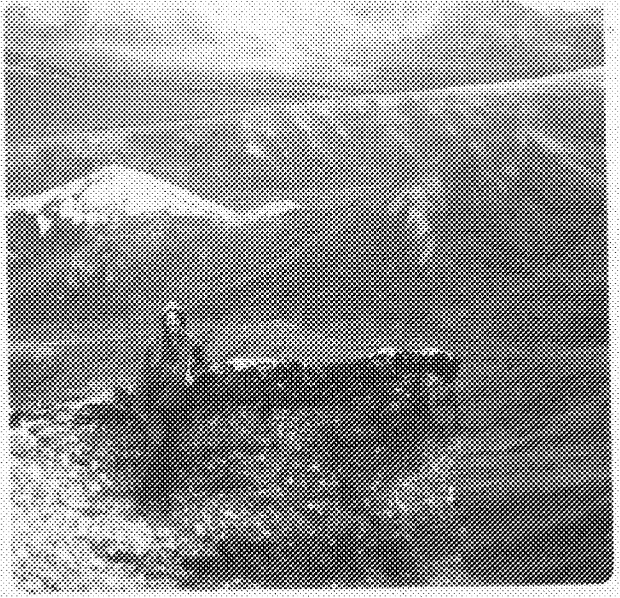

Figure 5. Paleocene Cantwell Formation (Tc) forms hoodoos in southeast corner of area about 2.5 miles south of mile 8.0 on the park road in SW/4 NW/4 NE/4 Sec. 29, T. 14 S., R. 8 W in the Healy C-5 quadrangle.

View to the north reveals light ridges of Cantwell Formation with the Birch Creek Schist of the Outer Range visible at the top of the picture.

Numerous dikes and small plutons cut this unit, many of which are apparently related to the volcanic upper member of the Cantwell Formation (Reed and Lanphere, 1961).

The lower detrital member of the Cantwell Formation is predominantly massive, coarse conglomerate with minor sandstone and rare argillite. This conglomerate shows high variability in size of clasts, percentage of clasts by volume, and matrix type. Rounded pebbles, averaging 1-3 inches in diameter and rarely greater than 6 inches, are contained in a poorly sorted, feldspathic, subangular, coarse sand matrix. In some very well indurated units, the pebbles seem to be molded against and impressed upon each other. This effect probably contributes to the Cantwell conglomerate's low porosity.

The types of pebbles comprising the conglomerate vary significantly from place to place; observations are summarized in Figure 6. This variability suggests very localized source areas for this unit. In the study area, white quartz, gray quartzite and igneous rocks comprise the bulk of the clasts. West of Sable Pass in Mount McKinley National Park, however, limestone and phyllite are prominent (Wahrhaftig, 1970b), supporting the generalization about local sources.

Pale yellowish-brown to medium light gray sandstones, poorly sorted, with angular to subangular grains are typical of the Cantwell Formation. In thin section, the abundance of lithic fragments and feldspars reveals a high degree of compositional immaturity paralleling the textural immaturity of this unit. Some exposures of thin-bedded sandstone display cross-bedding in 2-foot sets; in one locality on the western flank of Double Mountain, cross-bedding is even developed in coarse conglomerate.

Figure 6. Pebble counts from conglomerates of the Cantwell Formation

Pebble Type			Locality				
	1	2	3	4	5	Total	%
black argillite	4				2	6	1.4
gray argillite	2					2	.5
black slate		4	3	6	3	16	3.8
gray slate	1					1	.2
red shale			1			1	.2
black phyllite		5	5			10	2.4
gray phyllite	3	3	4	1		11	2.6
white phyllite			1			1	.2
red phyllite			1			1	.2
black chert	3	6	7	3	3	22	5.2
gray chert	3	1	3			7	1.6
red chert	1	3	1	3		8	1.9
green chert			1			1	.2
gray quartzite	10	28	19	26	4	87	20.5
green quartzite			1		3	4	.9
red quartzite			1			1	.2
black quartzite				2		2	.5
gray sandstone	1				16	17	4.0
black sandstone					2	2	.5
green sandstone					2	2	.5
green conglomerate					3	3	.7
gray felsite	3	3	7		2	15	3.5
felsite porphry	2					2	.5
green felsite		4	2	17		23	5.4
red felsite		1	2	2		5	1.2
black basalt					21	21	5.0
white quartz	17	42	42	49	3	143	33.8
	50	100	101	109	64	424	97.6

Localities:

1) NE/4 NW/4 NE/4 Sec. 6, T. 15 S., R. 9 W.; count taken near the base of Cantwell Formation, 5.3 miles S of fault.
2) SW/4 NE/4 SW/4 Sec. 5, T. 15 S., R. 10 W.; count taken near the base of Cantwell Formation, 5.4 miles S of fault.
3) SE/4 SE/4 NE/4 Sec. 5, T. 15 S., R. 10 W.; count taken about 200 feet above base of Cantwell Formation, 5.4 miles S of fault.
4) SW/4 NW/4 NE/4 Sec. 29, T. 14 S., R. 8 W.; count taken about 200 feet above base of Cantwell Formation, 3 miles S of fault.
5) SW/4 NW/4 SE/4 Sec. 21, T. 15 S., R. 10 W.; count taken several hundred feet above base of section

At each locality, 50-100 pebbles on the outcrop surface were broken and examined. Only pebbles >1/2 inch in diameter were counted; maximum diameter encountered was 6 inches. Volume of rock analyzed was approximately 600 cubic inches, but this varies with clast size.

The least abundant lithology is dark gray argillite, laminated and up to 30 feet thick. Not as conspicuous in the study area as elsewhere, this argillite contains the rusty traces of plant fragments. Elsewhere, identifiable plant fragments recovered from this unit provide a basis for age assignment.

The sedimentary member of the Cantwell Formation was laid down in a subsiding continental basin along the axis of the present Alaska Range. The absence of any marine fossils and the presence of land plants and coal document this continental environment. The large volume of poorly sorted, immature sedimentary rock suggests very rapid transport and deposition with little or no reworking. The most likely modern analogs to this depositional environment are alluvial fans, bajadas, and lacustrine deltas. White quartz and gray quartzite pebbles, probably from the Birch Creek Schist, suggest the northern foothills as a major source area. The limited cross-bedding measurements can neither support nor disprove a source to the north. The prominence of igneous clasts near the parent intrusions and the presence of chert and slate clasts near the Paleozoic metasedimentary sequence emphasize the importance of local sources.

The age of the sedimentary member of the Cantwell Formation has been established as Paleocene (Wolfe and Wahrhaftig, 1970) on the basis of well-preserved plant fragments in argillite beds.

The upper member of the Cantwell Formation in the study area contains an estimated 2000 feet of volcanic rocks; these rocks are absent in the type area. A succession of flows with minor interbeds of pyroclastic and sedimentary rocks crops out on the tops of Double Mountain and Igloo Mountain (see Figure 7). From a distance the tan volcanic rocks can be easily distinguished from the darker sedimentary sequence.

These pale olive to grayish green flows, 10-60 feet thick, have vesicular tops with chalcedony and quartz amygdules. Interflow sandstones with abundant volcanic fragments are included in this volcanic pile. The contact with the sedimentary member below appears to be conformable, or perhaps only slightly disconformable. No evidence was seen for discordance of structural trends or an erosion surface on the top of the sedimentary sequence.

Basalt and basaltic andesite compositions are most prevalent from thin section analysis. Two samples were analyzed chemically and dated radiometrically (see appendices); the following thin section data were recorded from visual inspection of specimens which were age dated and chemically analyzed. All percents are visual estimates.

Specimen UW 1562/3, basalt from Double Mountain:

60%	oriented plagioclase laths and one phenocryst, euhedral to subhedral, albite-Carlsbad twinned and up to 0.5 mm, An_{52} from extinction angles
5%	anhedral olivine up to 0.2 mm, rimmed by alteration products, some pseudomorphs of serpentine after olivine
15%	pyroxene up to 0.01 mm
10%	brown gray glass
5%	anhedral opaques, dominantly magnetite
5%	alteration products, including zeolite, sericite, chlorite, serpentine

Figure 7. Double Mountain viewed toward the east from Igloo Mountain.

The best exposures of Paleocene Cantwell Formation (Tc) in the study area are here; dashed line divides upper volcanic member from lower sedimentary member.

Figure 7. Double Mountain viewed toward the east from Igloo Mountain.

The best exposures of Paleocene Cantwell Formation (Tc) in the study area are here; dashed line divides upper volcanic member from lower sedimentary member.

Flow structure is striking in this fine-grained, intergranular basalt.

Specimen UW 1562/4, basaltic andesite from Igloo Mountain:

60%	subhedral plagioclase laths up to 2 mm, albite-Carlsbad twinned and bent, An$_{50-68}$, from extinction angles.
20%	serpentine, from alteration of mafic minerals
5%	opaque needles up to 1 mm
5%	calcite, locally in veins
5%	zeolites, sheaf-like aggregates filling cavities
5%	sericite, widespread, incipient plagioclase alteration

No flow structure is present; the interlocking plagioclase grains form an intersertal texture.

Although highly jointed basalt and basaltic andesite flows are the most common, other igneous compositions and textures are also present (see Figure 8). Pale yellowish brown rocks, probably rhyolite in composition, crop out near the top of Double Mountain; grayish orange pyroclastic rocks are associated with them. The deeply weathered yellow zone seen in the profile of Double Mountain contains a most interesting material. A porous rock originally, possibly a scoria or tuff zone, chemical weathering has reduced it to hydroplastic clay.

Although the sedimentary rocks of the Cantwell Formation have been dated as Paleocene, little information on the age of the volcanic rocks has been available. However, two specimens dated by potassium-argon methods, UW 1562/3 and UW 1562/4, have furnished ages of 55.1 ± 2.3

Figure 8. Successive basalt flows cropping out on the top of Double Mountain. This is the volcanic member of the Paleocene Cantwell Formation (Tv).

Note lighter rhyolite body and 120 feet of more mafic flows.

View is to the east; location is NW/4 SE/4 NW/4 Sec. 22, T. 15 S., R. 10 W. of the Healy C-5 quadrangle.

Figure 8. Successive basalt flows cropping out on the top of Double Mountain. This is the volcanic member of the Paleocene Cantwell Formation (Tv).

Note lighter rhyolite body and 120 feet of more mafic flows.

View is to the east; location is NW/4 SE/4 NW/4 Sec. 22, T. 15 S., R. 10 W. of the Healy C-5 quadrangle.

and 59.3 ± 2.7 million years respectively (see Appendix 2). These results suggest a late Paleocene to early Eocene age for the volcanic member.

The lava flows of the Cantwell Formation were deposited in an environment very similar to that of the Cantwell conglomerate. A continental basin is a very likely setting. The lack of pillow structure in the flows or good grading in the pyroclastics suggests subaerial deposition. Possible sources for these flows have not been found within the study area, and flow direction data are insufficient for reasonable conjecture.

Oligocene to Miocene coal-bearing group (Tcb), sandstone, claystone, conglomerate and sub-bituminous coal.

In the low rolling valley which drains into the Savage River, gullied cuestas are weak topographic expression of the Tertiary coal-bearing group. An unconsolidated unit which is easily eroded, this group occupies lowlands on the north boundary of the area and in a belt curving southward and southwestward from the Savage River bridge. Wahrhaftig and others (1969) divide this group into 5 formations, one of which occurs extensively in the study area, the Healy Creek Formation. For purposes of this study, these divisions have not been used; this middle Tertiary group will be considered as a whole.

This group overlies the Cantwell Formation with angular unconformity; the Nenana Gravel overlies it with structural concordance but stratigraphic unconformity. On the north side of the Outer Range, the coal-bearing group rests in depositional contact upon the Birch Creek Schist.

Similar relations with the Paleozoic metasedimentary unit probably occur, but cannot be demonstrated south of the Hines Creek fault. In the study area, thickness is difficult to judge but is probably on the order of 600 feet. In the type locality at Suntrana, northwest of the study area, this group is on the order of 2000 feet thick (Wahrhaftig, 1958).

Poorly indurated to unconsolidated quartz-pebble gravel typifies this unit in the study area. Cuestas of the conglomerate units of this group are massively bedded while the sandstones are thin-bedded. Invariably, conglomerate outcrops are brilliant white due to their composition of 99 percent subrounded, white quartz pebbles in a fine sand matrix. Clasts usually make up about 50 percent of the rock volume and are no bigger than 2 inches long. Minor coal interbeds are dusky brown, sub-bituminous with plant debris preserved (see Figure 9).

The Tertiary coal-bearing group gradually buried a fairly rugged topography by valley-filling (Wahrhaftig, 1969). Like the Cantwell Formation, this also is a continental deposit. The patchy distribution of this unit implies that it was deposited in lowlands closely related to present topographic lows and that it was locally derived. This local derivation is particularly striking north of the Outer Range where the coal-bearing group laps up onto the Birch Creek Schist. The quartz-sericite schist there is cut by numerous white quartz veins; the Tertiary deposits consist of white quartz pebbles embedded in a matrix of quartz sand.

Plant macrofossils, as well as spore and pollen assemblages, have been used to date the coal-bearing group. The best age estimates range

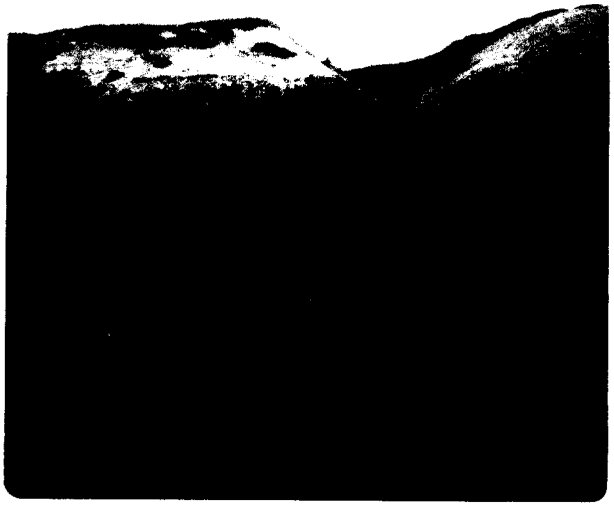

Figure 9. Ten-foot thick coal seam (black) dips gently northward in the Tertiary coal-bearing group (Tcb), located 2.5 miles northward down Savage River from Savage River bridge on the park road. Flat-lying gravels overlying the coal unconformably are Quaternary alluvium (Qs).

View is to the west in NW/4 SE/4 SE/4 Sec. 17, T. 13 S, R. 9 W. in the Healy D-5 quadrangle.

Figure 9. Ten-foot thick coal seam (black) dips gently northward in the Tertiary coal-bearing group (Tcb), located 2.5 miles northward down Savage River from Savage River bridge on the park road. Flat-lying gravels overlying the coal unconformably are Quaternary alluvium (Qs).

View is to the west in NW/4 SE/4 SE/4 Sec. 17, T. 13 S., R. 9 W. in the Healy D-5 quadrangle.

from late Oligocene through late Miocene (Wahrhaftig, 1969). The part of this group present in the study area, however, may span only the earlier half of this time interval.

Pliocene (?) Nenana Gravel (Tn), conglomerate and sandstone.

The rolling plains and valleys of the central lowland in the study area are underlain by Nenana Gravel. This unit is best exposed north of the study area but can be seen supporting cuestas and low plateaus south of the park road between the Savage and Teklanika Rivers. Its poorly cemented nature permits rapid weathering and a heavy cover of vegetation, so the structure is decipherable only where physiographic expression is great or where rivers have cut down through it. The Nenana Gravel appears more resistant to weathering than the older coal-bearing unit since it forms extensive hogbacks on the extreme north and northwest margins of the area. Wahrhaftig (1970a) attributes this resistance to the coarse grain size and permeability of this upper Tertiary formation.

In its type area between Healy and Lignite Creeks on the east bank of the Nenana River, the Nenana Gravel has a total thickness of 4,000 feet (Wahrhaftig and Black, 1958), but it is probably considerably thinner within the McKinley Park area because of erosion. This formation lies with structural concordance but possible stratigraphic unconformity upon the Tertiary coal-bearing group. Elsewhere, there is evidence of angular unconformity between the two units (Wahrhaftig and Black, 1958). Where the coal-bearing group is absent, the Nenana Gravel is unconformable upon older rocks; in the extreme northern part of the study area, for example, it laps up onto the Birch Creek Schist.

The Nenana Gravel is a moderately consolidated but poorly cemented pebble, cobble, and boulder conglomerate. Rounded clasts from 1 inch to 1 foot long rest in a coarse sand matrix. Iron oxide staining of clasts and matrix is very prevalent, causing the overall aspect of gravel outcrops to be dark yellowish orange when dry or moderate reddish brown when wet. Most clasts in this unit are deeply weathered, with 1-inch rinds. Clast compositions include numerous intrusive igneous rocks, quartzite, conglomerate, and other sedimentary rocks. Minor interbeds of light gray silty sandstone and bituminous coal serve to delineate bedding in this massive unit.

Like the older Tertiary formations, the Nenana Gravel is a continental deposit. Its coarse nature, and its textural and compositional immaturity, demonstrate brief transport and rapid deposition in a low energy environment. Studies of pebble composition, pebble population, clast size, and paleocurrents by Wahrhaftig (1970c) show that this unit represents a bajada formed by northward-flowing streams heading in the southern and middle Alaska Range.

Always regarded as Tertiary, the Nenana Gravel has recently been assigned to the Pliocene (?) (Wahrhaftig, 1970c). Radiometric dating of a tuff in the coal-bearing group has provided a minimum age of 8.1 million years (Wahrhaftig and others, 1969), but a late Miocene flora was also found in this underlying formation. On the basis of this information, a Pliocene (?) age for the Nenana Gravel seems highly plausible.

Quaternary Sediments (Qs), glacial deposits, colluvium, alluvial fans and terrace deposits.

Although much of the map area is covered by Quaternary unconsolidated deposits, these flat-lying, totally undeformed units offer little to the tectonic analysis of the area. No attempt was made to subdivide these deposits or to distinguish Holocene sediments from older Pleistocene glacial deposits.

IGNEOUS ROCKS

Paleozoic (?) gabbro (Pg)

Trending approximately east-west, low, rounded ridges of medium- to coarse-grained gabbro define two linear plutons as much as 6 miles in length. One body is located on the western edge of the study area and crosses the Teklanika River just north of the campground; the other crops out in the southeast part of the area, approximately 2.5 miles south of the Savage River campground. They may actually be one pluton, but this cannot be demonstrated by surface mapping. In addition to these major plutons, there are also numerous minor bodies of similar composition up to 1 mile in length.

The Paleozoic (?) gabbro cuts only the Paleozoic slate and associated rocks. The main gabbro bodies appear to be for the most part structurally concordant with the folded slate; however, "baked zones" at the contact, near Teklanika campground, for example, obscure this relation. This igneous unit only occurs south of the Hines Creek fault.

Commonly dark greenish gray to greenish black in color, these medium- to coarse-grained rocks are hypidiomorphic-granular in texture with minor porphyritic varieties. Joints and shear fractures cut the gabbro locally, with calcite and sulfide veining in some. Well developed plagioclase laths are characteristically visible in hand specimen.

Two representative specimens were selected for radiometric dating and chemical analysis (see appendices). Petrographically, specimen UW 1562/1 is estimated visually to be:

60%	subhedral plagioclase laths up to 0.5 mm, totally altered to sericite
25%	ragged anhedral augite, interstitial
5%	opaque minerals, probably magnetite, anhedral
5%	amphibole associated with pyroxene
5%	fibrous serpentine from the breakdown of pyroxene

Thin section analysis of UW 1562/2 yielded similar results:

55%	plagioclase phenocrysts up to 4 mm, totally sericitized
25%	anhedral, twinned augite, to 0.5 mm, interstitial
10%	opaque minerals, proably magnetite
10%	serpentine

Both these specimens have conspicuous cataclastic textures present. Pyroxenes are commonly grouped into clots, and 1 mm aggregates of quartz grains are present. The high degree of alteration of plagioclase, although precluding a definite compositional determination, does imply highly calcic plagioclase since sericitization only attacks the anorthite portion. Ophitic pyroxenes about plagioclase are widespread in coarse-grained specimens.

Contact relations provide little control for the age of this unit since fossil evidence for the age of the host metasedimentary rocks is lacking. The Paleocene Cantwell Formation is not cut by the gabbro, but this does not eliminate much of geologic time. Potassium-argon age determinations on Specimens UW 1562/1 and UW 1562/2, however, yielded ages of 359 ± 44 and 329 ± 30 million years respectively. UW 1562/1 was collected approximately 3 miles south of Savage River campground, while UW 1562/2 was obtained about 4 miles west of Teklanika River campground.

Several problems hinder interpretation of the radiometric age measurements. First, metamorphism, so visible in other units, may have reset the radioactive "clocks". The age measurements would in this case reflect the metamorphic event rather than the earlier igneous intrusion. Second, although later thermal effects may not have been severe enough to affect the critical isotope ratios, purely mechanical shearing may have released some argon, resulting in erroneously low ages. Third, the materials analyzed, pyroxene concentrates and gabbro whole rock samples, are extremely low in potassium content; uncertainties in potassium-argon dating are most evident for minerals with low potassium values. Fourth, the dates obtained cannot even be regarded simply as minimum ages since pyroxene ages are commonly high due to the effect of excess Ar^{40} (Damon, 1968). Finally, other workers (Reed and Lanphere, 1970) have so far recognized no plutons younger than Jurassic in the central Alaska Range.

The dated plutons, plus other mafic rocks of similar texture, are here designated tentatively as Paleozoic (?). The age measurements are probably close to an igneous rather than metamorphic age, since the prevailing metamorphic grade is quite low. Errors due to argon loss and excess argon are both possible; therefore, the total error cannot be judged quantitatively. The abundance of plutons and the limited isotopic data make the argument from other age dates less forceful. After consideration of the shortcomings and appreciating the close agreement between mid-Paleozoic ages obtained, an age assignment of Paleozoic (?) is made as the best working approximation from the data available.

Tertiary mafic to intermediate intrusives (Ti)

Many small dikes and plugs, tens to hundreds of feet in size and varying in composition, cut the Cantwell Formation and the Birch Creek Schist. A dike of basaltic composition discordantly intrudes the Birch Creek Schist in the extreme northeastern part of the area. Small plugs and dikes are located in the Cantwell Formation 3 miles east of the Teklanika River bridge and on the north flank of Igloo Mountain.

Grayish olive green but weathering to yellow browns, these fine- to medium-grained plugs have been grouped together for mapping purposes. Intrusive relations date these rocks as early Tertiary since they cut the Cantwell Formation; potassium-argon dating of a dike in the Birch Creek Schist to the east (Bultman, 1972) also disclosed an early Tertiary age.

DESCRIPTIVE STRUCTURAL GEOLOGY

Introduction

A main purpose of this study is to obtain a number of structural measurements in the area around the Hines Creek fault; this detailed mapping should provide a picture of the history of deformation. From the strain recorded by structures in the various map units will emerge a reconstruction of the stress fields acting through time in the northeastern Mount McKinley National Park area.

As the structural data were plotted, several parallel trends became apparent. Although the main trend of the Alaska Range is approximately N 76° E, in the study area the foothills undergo a local bending. East of the Teklanika River, the schist terrane trends N 87° E, but west of the river, its strike changes to N 69° E. The structural elements present in the Birch Creek Schist follow this change, as does the Hines Creek fault. This bending around is less demonstrable in younger units, but folds in the Paleozoic and Tertiary rocks follow closely the east-west regional pattern of the Alaska Range.

In contrast to this gross similarity in trend, great variation in intensity of deformation exists among the mapped units. Structural style grades, with increasing age, from gentle dips and open folds in the Tertiary deposits to intense folding, foliation, and cleavage in the Birch Creek Schist.

Large-scale folds

Large amplitude folds with half-wave lengths on the order of a mile or more have been created in the Tertiary units. Gently plunging axes and west-trending axial planes are the rule in these gentle, open folds. Good examples of this mode of deformation occur at Igloo Mountain, a northeastward-plunging syncline in Cantwell volcanic rocks, and at the broad plain between the Savage and Sanctuary Rivers, which contains several folds in the Tertiary coal-bearing group and Nenana Gravel.

Folds in the poorly consolidated Tertiary units (Tcb and Tn) are interpreted from physiographic features and sparse outcrops. Besides questionable minor folds, the arcuate outcrop pattern of the two units suggests a broad syncline with a half-wave length of at least 2 miles. The best approximation for the trend of this feature is N 75° E, very close to the regional strike of the range. The maximum dip observed in these units is 40° on the north flank of the range (see Figure 10).

The Cantwell Formation and the unconformity surface upon which it was laid down are warped into large, cylindroidal, open folds throughout the study area (see Figure 11). Trending east-west in the area's southeastern corner, these symmetric folds usually display vertical axial planes and half-wave lengths of 1/2 mile. In the southwestern part of the area, just as the foothills adopt a more northeasterly strike, so do the axial planes of folds in the Cantwell Formation. The N 51° E trend of the Igloo Mountain Syncline and the N 63° E syncline east of the Teklanika River bridge illustrate this change. Parallel, open folds are most common, but the Cantwell Formation is chevron-folded and warped into nearly ver-

Figure 10. Hogbacks and hills of the Tertiary coal-bearing group display moderate to steep northerly dips, north of the Outer Range.

View is to the east in the extreme northeast corner of the study area; photograph from NW/4 NW/4 NE/4 Sec. 3, T. 13 S., R 9 W. in the Healy D-5 quadrangle.

Figure 10. Hogbacks and hills of the Tertiary coal-bearing group display moderate to steep northerly dips, north of the Outer Range.

View is to the east in the extreme northeast corner of the study area; photograph from NW/4 NW/4 NE/4 Sec. 3, T. 13 S., R 9 W. in the Healy D-5 quadrangle.

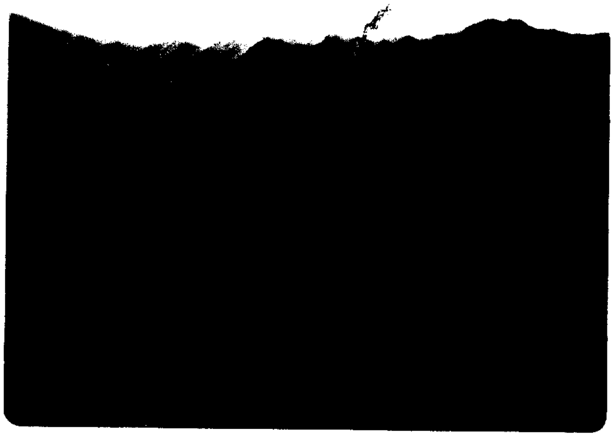

Figure 11. Folded angular unconformity between Paleozoic (?) metasedimentary rocks, (Pz), and the Paleocene Cantwell Formation, (Tc), located 4 miles west of a point 1 mile north of Igloo Creek campground on the park road.

Beds on the left are south-dipping Cantwell Formation sedimentary rocks which overlie the steeply north-dipping Paleozoic metasedimentary rocks unconformably.

View is to the west of NE/4 NE/4 NE/4 Sec. 17, T. 15 S., R. 11 W. in the Healy C-6 quadrangle.

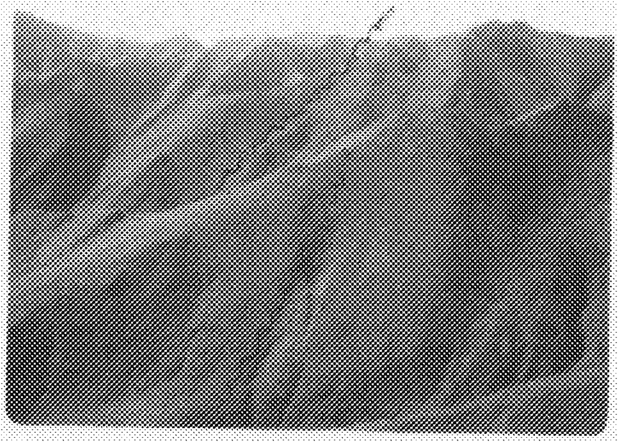

Figure 11. Folded angular unconformity between Paleozoic (?) metasedimentary rocks, (Pz), and the Paleocene Cantwell Formation, (Tc), located 4 miles west of a point 1 mile north of Igloo Creek campground on the park road.

Beds on the left are south-dipping Cantwell Formation sedimentary rocks which overlie the steeply north-dipping Paleozoic metasedimentary rocks unconformably.

View is to the west of NE/4 NE/4 NE/4 Sec. 17, T. 15 S., R. 11 W. in the Healy C-6 quadrangle.

tical positions locally. One example of slight overturning is present in an asymmetric syncline near the head of Big Creek (NW/4 SW/4 SE/4 Sec. 10, T. 15 S., R. 11 W. in the Healy C-6 quadrangle).

Small-scale folds

Small-scale folding is quite intense in the Pre-Tertiary units, the Paleozoic (?) slate and associated rocks and the Precambrian (?) Birch Creek Schist. Stratigraphic sequence in the slate is largely obscured by folds with 1-foot half-wave lengths and amplitudes many times this. Similarly, in the Birch Creek Schist, folds with 1-foot to 20-foot amplitudes make it impossible in places to discern the true dip of bedding. Both units contain folds even on the microscopic scale.

Folds in the Paleozoic slate are very tight to isoclinal in a representative outcrop (see Figure 12). In the dozen or so folds clearly recognized in the study area, 20-foot wave lengths and vertical axial planes are most prevalent. Trends of the axial planes exhibit considerably more scatter than those of other units but are mostly within 30° of east-west. Problems were encountered in measuring attitudes due to this unit's tendency to slumping; amplitude estimates are hampered by poor exposures but are at least several times the observed half-wave length. Dips of bedding in the Paleozoic (?) slate are generally quite steep except where influenced by creep or slumping. Igneous plutons of Paleozoic (?) gabbro exhibit approximate structural concordance with the trend of these folds.

The most intensely folded unit is the Birch Creek Schist; many types of open, chevron, similar and parallel folds have been formed

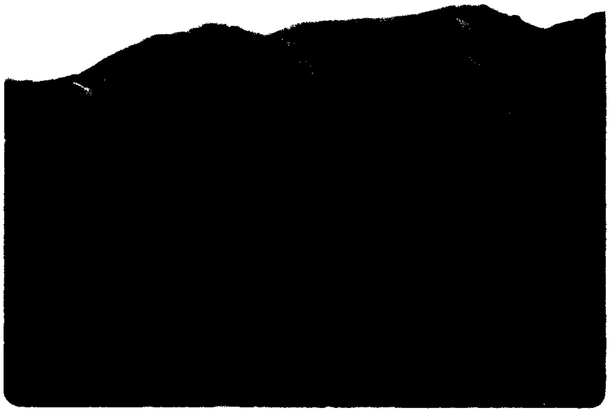

Figure 12. Nearly isoclinal anticline in Paleozoic (?) slate located 3 miles south of mile 10.0 on the park road, in the southeastern corner of the study area. Distant ridge is capped by Cantwell Formation.

View is to the southeast of NW/4 NE/4 NE/4 Sec. 36, T. 14 S., R. 9 W. in the Healy C-5 quadrangle.

Figure 12. Nearly isoclinal anticline in Paleozoic (?) slate located 3 miles south of mile 10.0 on the park road, in the southeastern corner of the study area. Distant ridge is capped by Cantwell Formation.

View is to the southeast of NW/4 NE/4 NE/4 Sec. 36, T. 14 S., R. 9 W. in the Healy C-5 quadrangle.

in S_1, the primary foliation of these rocks. Amplitudes comprise the whole spectrum from 30 feet to less than 1 inch; wave lengths vary accordingly. The quartzose layers are generally thrown into open folds, but the less competent phyllitic strata form asymmetric drag folds and kink bands. A prominent axial plane fracture cleavage, S_2, assumes horizontal attitudes or dips gently south (see p. 53) in these recumbent folds. Concordant quartz veins are folded also; no clue was found as to whether their origin is pre- or post-folding.

The trends of the axes of these minor folds have been plotted on Figure 13. The average value, approximately a 5° plunge to N 80° E, is very close to the average trend of the range. If the axes are divided into domains east and west of the Teklanika River, the axes of the small-scale folds repeat the bend seen in outcrop pattern. In places where fold axes are exposed for a few yards, some show mild undulations; no generalization is warranted, however.

Thickening and thinning along the limbs of folds is not conspicuous except in the two limestone lenses encountered. Slip occurs along cleavage planes in the tighter folds.

Foliation

Planar parallelism of flakes of sericite and other micas define strong foliation in much of the Paleozoic (?) metasedimentary sequence and in all of the Birch Creek Schist. In both rock units, the primary foliation parallels the original bedding. In the more highly deformed Birch Creek Schist a second foliation has developed which cuts the

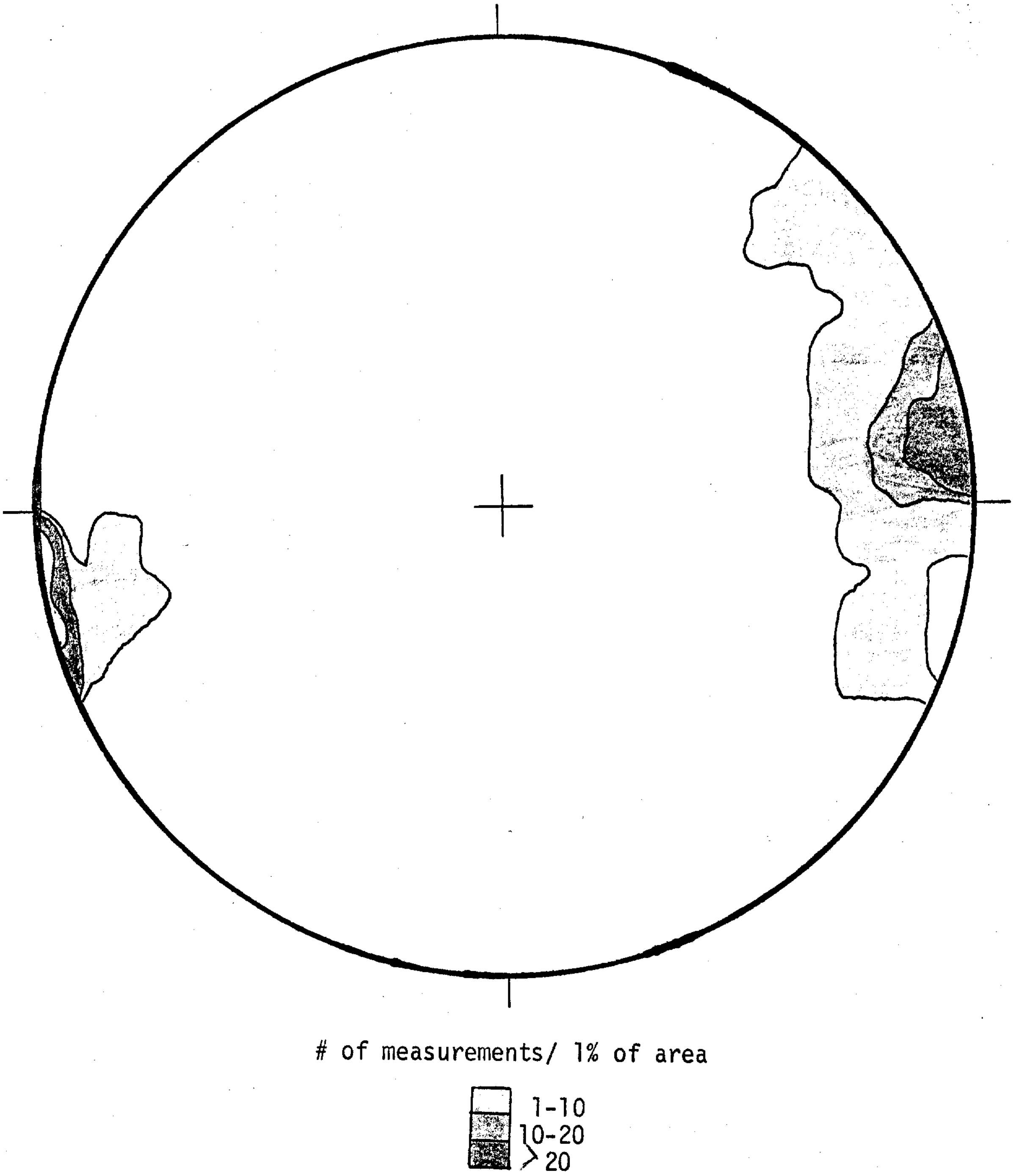

Figure 13. Equal-area net diagram of 80 minor fold axes in Birch Creek Schist.

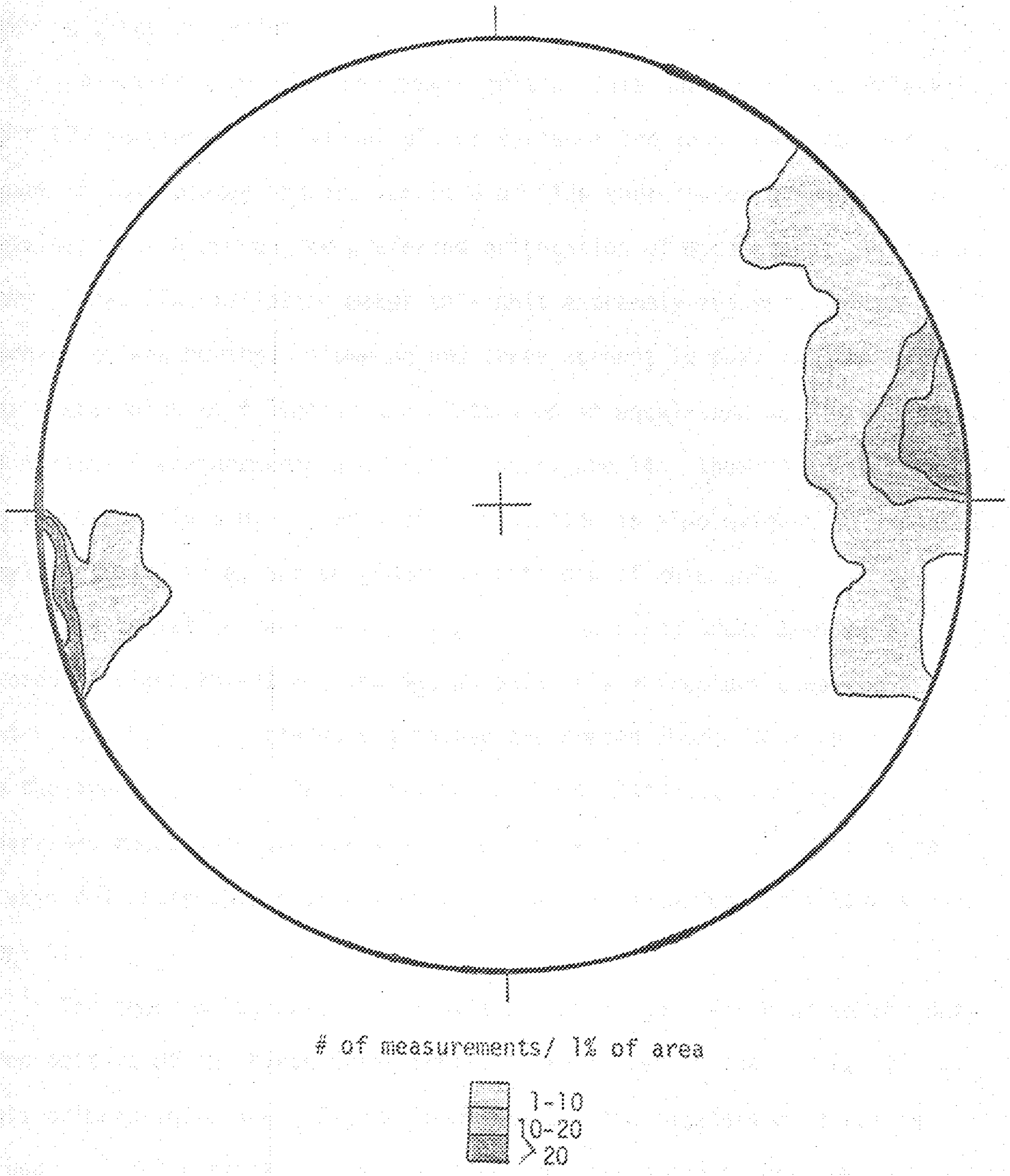

Figure 13. Equal-area net diagram of 80 minor fold axes in Birch Creek Schist.

bedding plane foliation.

Foliation is present everywhere in the slate portion of the Paleozoic (?) sequence. Individual planar surfaces are less than 1/8 inch apart in most places and are composed of fine sericite or graphite. In thin section, a pronounced preferred orientation of mica flakes parallels this plane. The foliation makes this unit extremely susceptible to mechanical weathering; slumping and creep account in part for the scatter where poles to foliation are plotted on an equal-area net (π diagram). 56 foliation measurements are plotted on Figure 14; their average trend is approximately N 81° E, 78°S dip. Foliation is also evident in isolated phyllite, sandstone, and conglomerate outcrops of this unit.

Two foliations are very prominent in the Birch Creek Schist, S_1, a bedding plane foliation, and S_2, an axial plane fracture cleavage which cuts S_1. S_1 surfaces are folded and spaced about 1/2 inch apart on the average; phyllite possess thinner microlithons, but highly quartzose rocks show greater spacing of foliation surfaces. Since mica flakes delineate this planar feature, mica-poor rocks commonly have very weak S_1.

The trend of S_1 defines the axis of the range. The bend in the outcrop pattern of the Birch Creek Schist is reflected in the strike of this primary foliation. Figure 15 brings out the clustering of points around a N 79° E strike. The dip is not so well grouped, but the majority of readings dip steeply south, from 60° - 90°. The explanation for this divergence is that the extensive foliation present in the schist leads to its being easily rotated out of place by mass wasting. Thus,

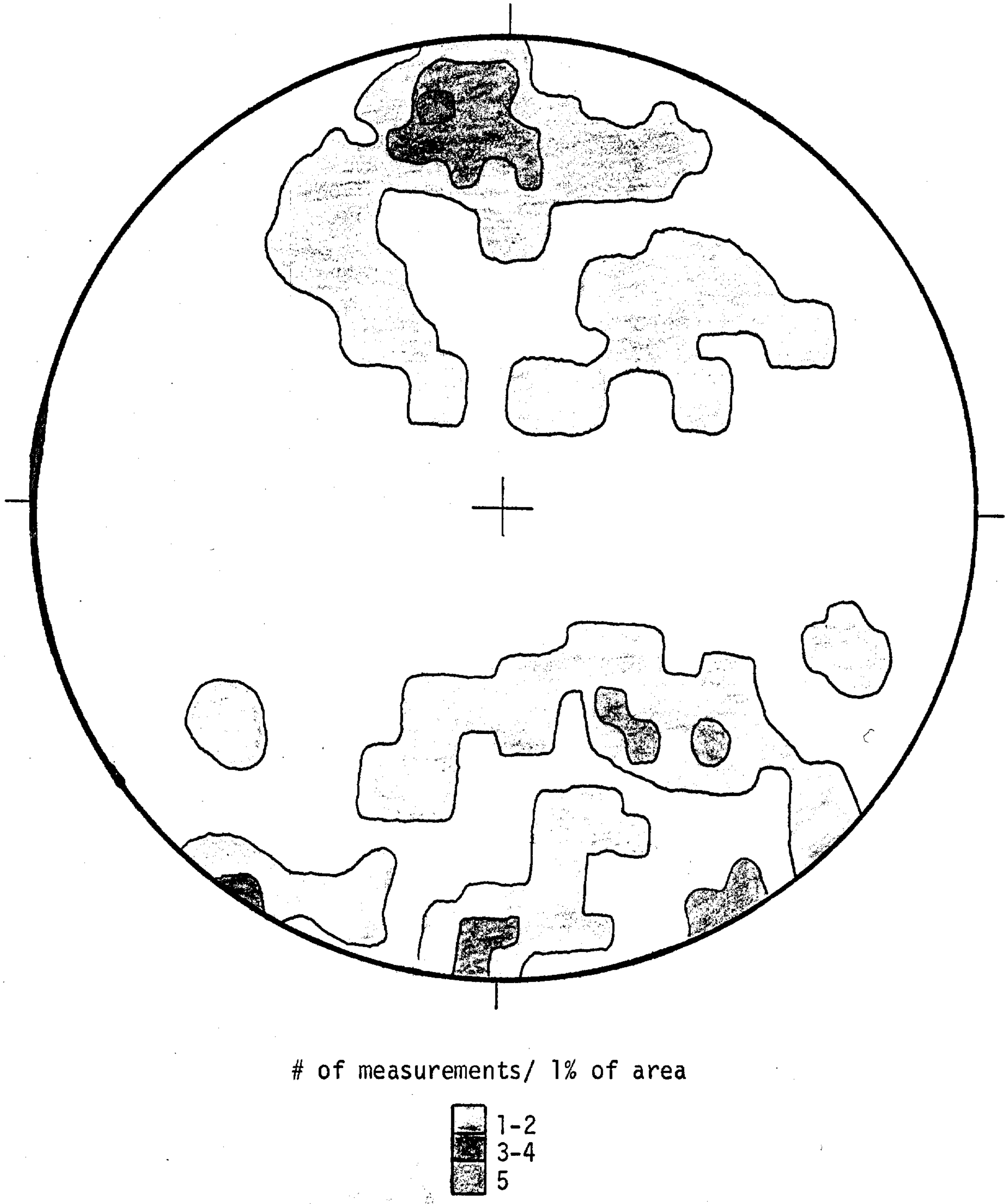

Figure 14. Equal-area net diagram of 56 poles to foliation in Paleozoic (?) slate unit (Pz).

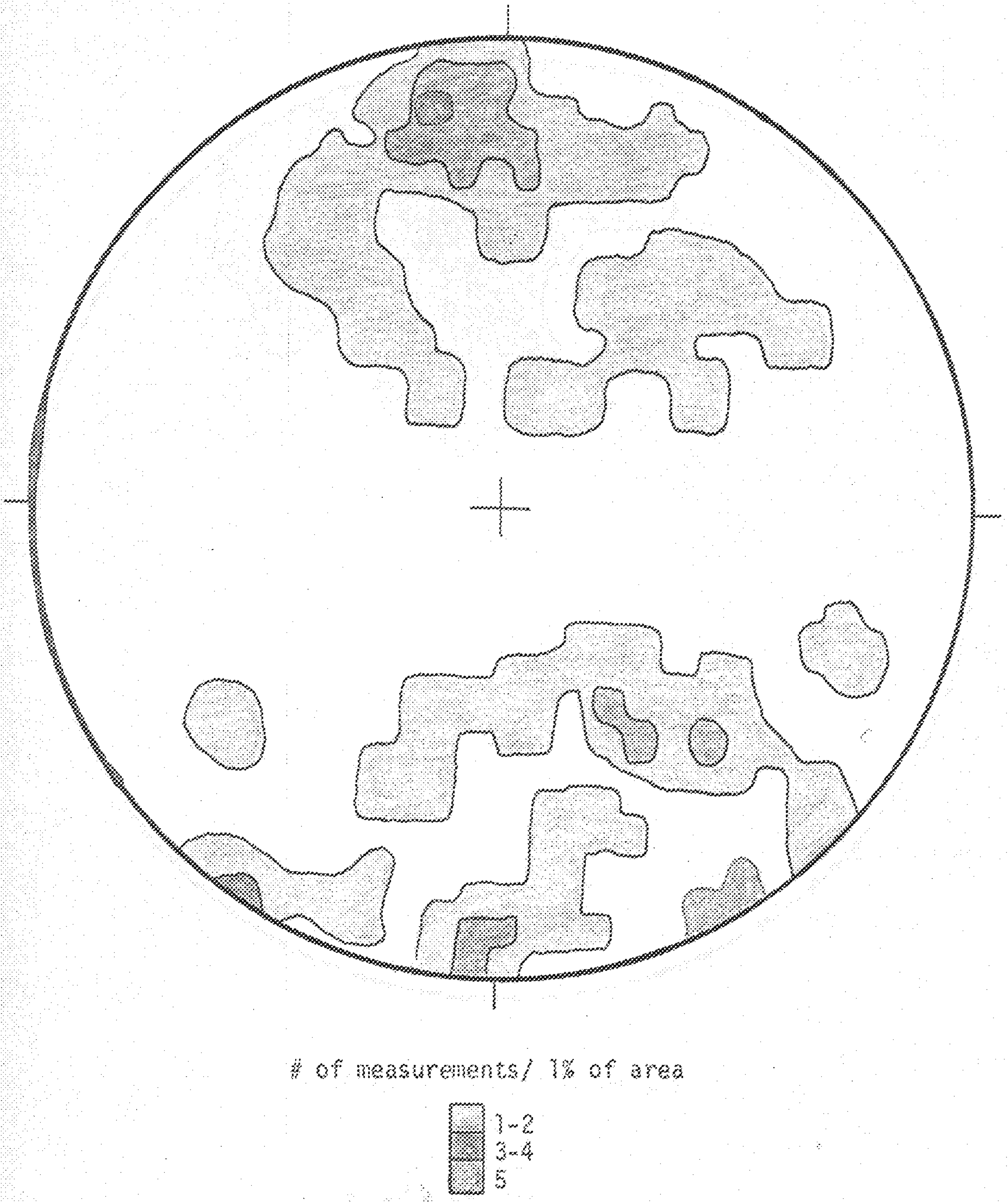

Figure 14. Equal-area net diagram of 56 poles to foliation in Paleozoic (?) slate unit (Pz).

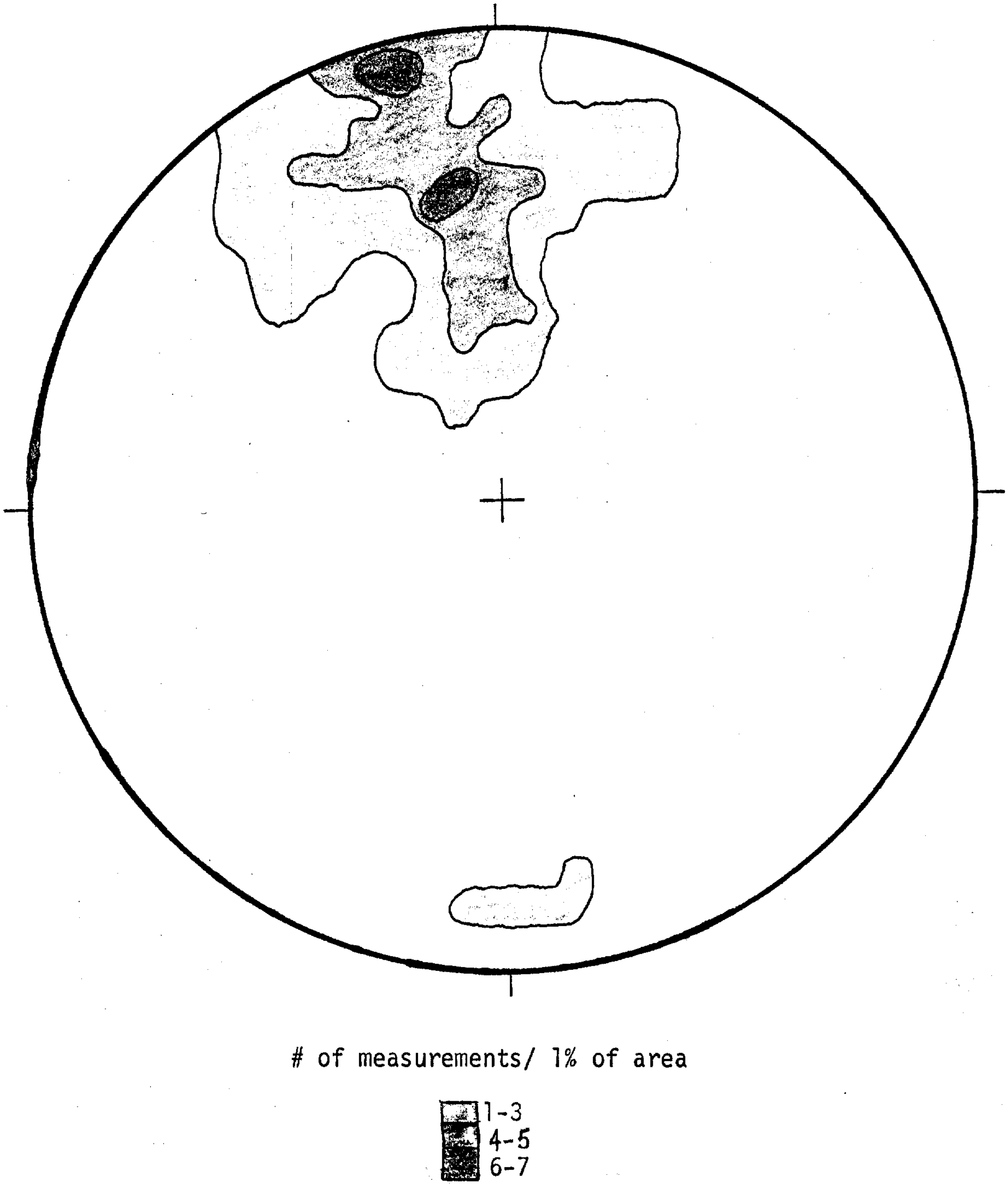

Figure 15. Equal-area net diagram of 61 poles to S_1 in the Birch Creek Schist.

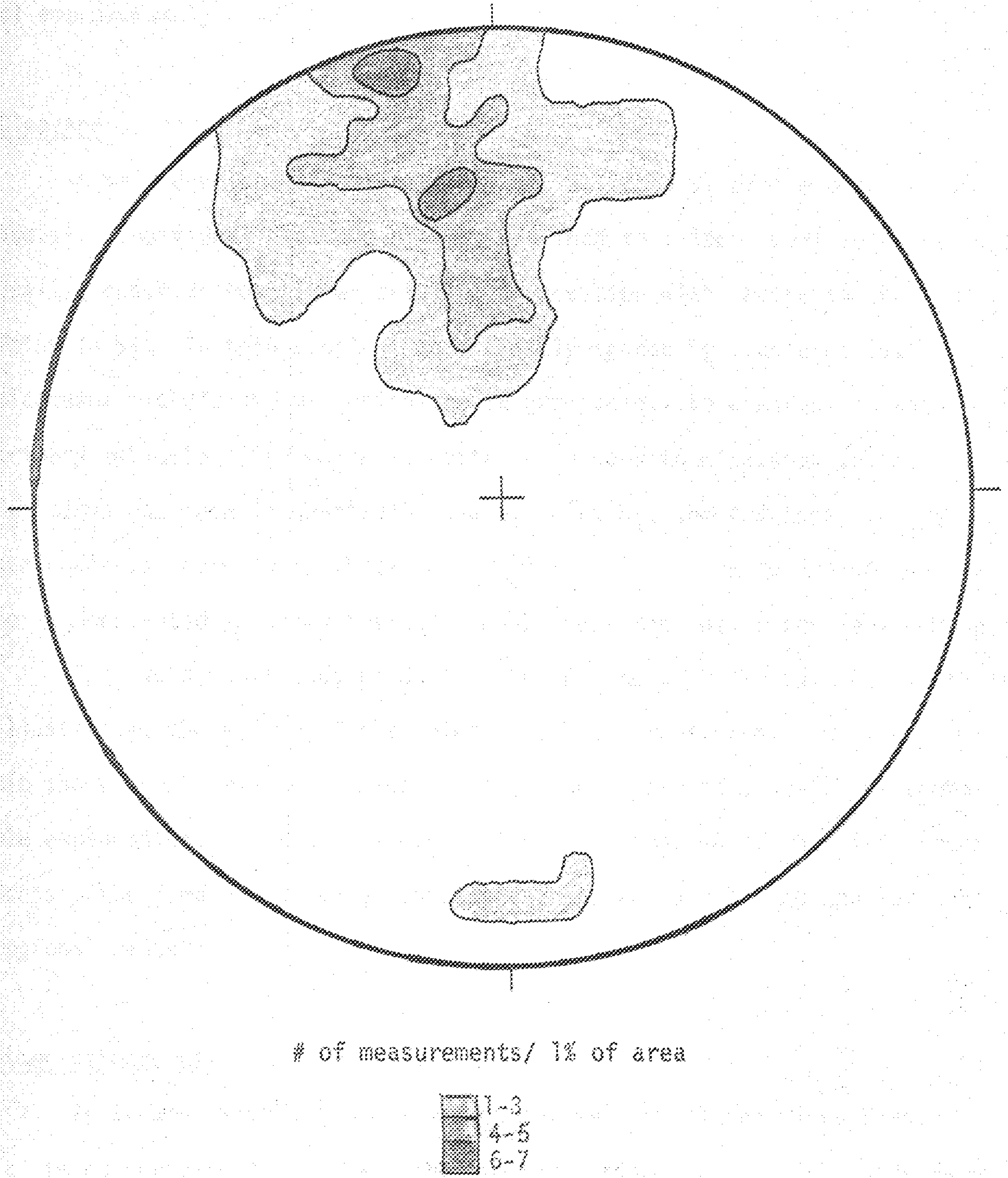

Figure 15. Equal-area net diagram of 61 poles to S_1 in the Birch Creek Schist.

one more structural element fits into the consistent regional attitude of approximately N 76° E.

Cleavage

A well developed fracture cleavage, S_2, cuts S_1 of the Birch Creek Schist. Individual cleavage planes, 1/4 inch to 1 inch apart mesoscopically, occur in roughly an axial plane position with regard to the minor folds in S_1. In thin section, more closely spaced S_2 fractures cut micaceous microfolds, mirroring the larger scale. In contrast to the primary foliation, S_1, which is better developed in micaceous units, S_2 stands out more in quartzose layers. Like S_1, the fracture cleavage surfaces are coated with fine-grained mica. Slip of up to an inch can be demonstrated in a few instances on S_2 surfaces but is not very common.

The average attitude of S_2 is N 80° E with a 12° S dip. As Figure 16 illustrates, the strike of this element is very consistent, but the dip shows more variation; mass wasting effects are once again the probable explanation. As with the other structural featues of the Birch Creek Schist, the fracture cleavage possesses a strike paralleling that of the regional pattern.

Other structures

In an area with such an abundance of well developed structures, it is no surprise that other minor features also occur. Kink bands were seen in a few exposures of Paleozoic (?) slate; their scarcity disqualifies them as useful intepretive tools. In addition, stretching of

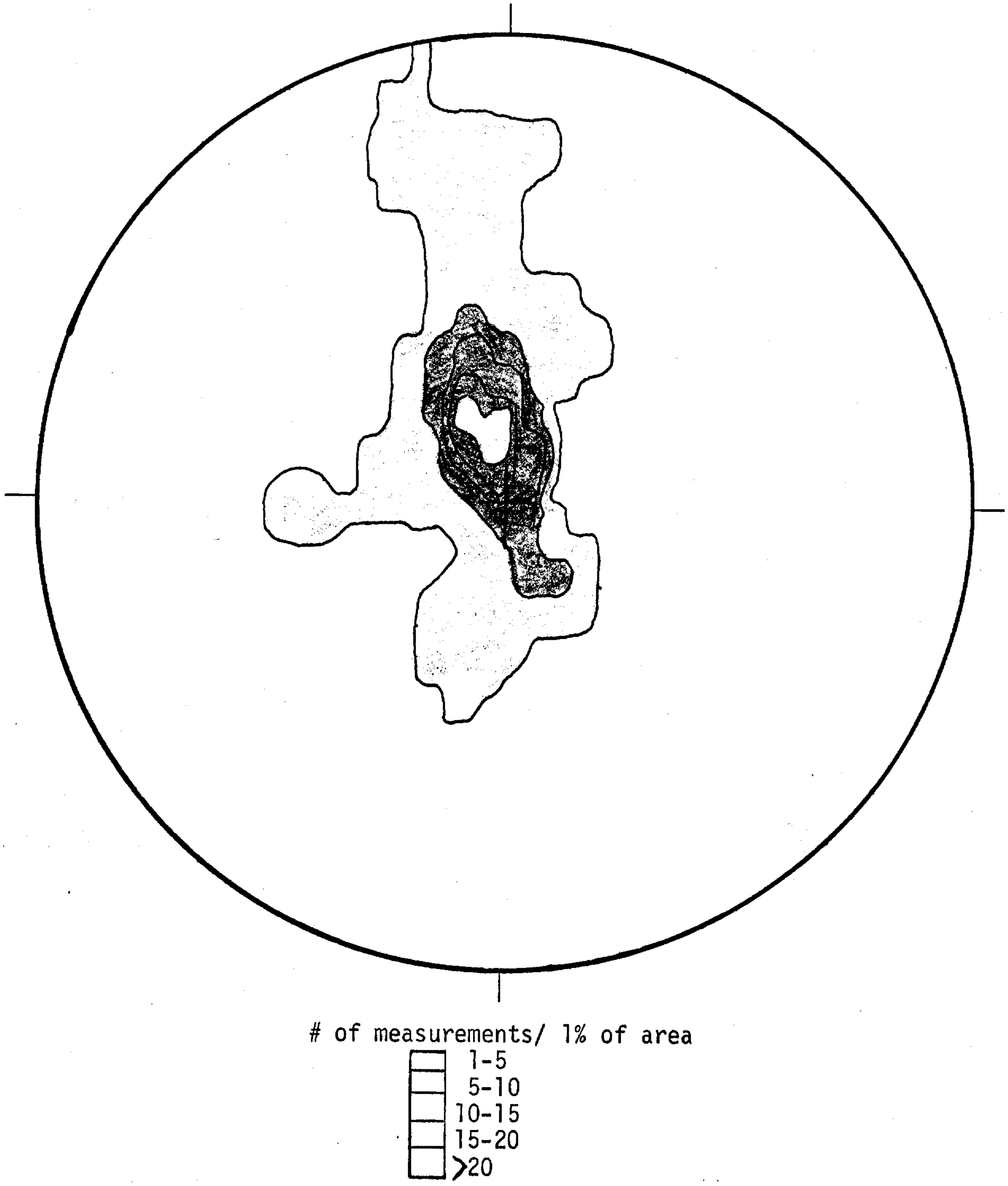

Figure 16. Equal-area net diagram of 84 poles to S_2 in the Birch Creek Schist.

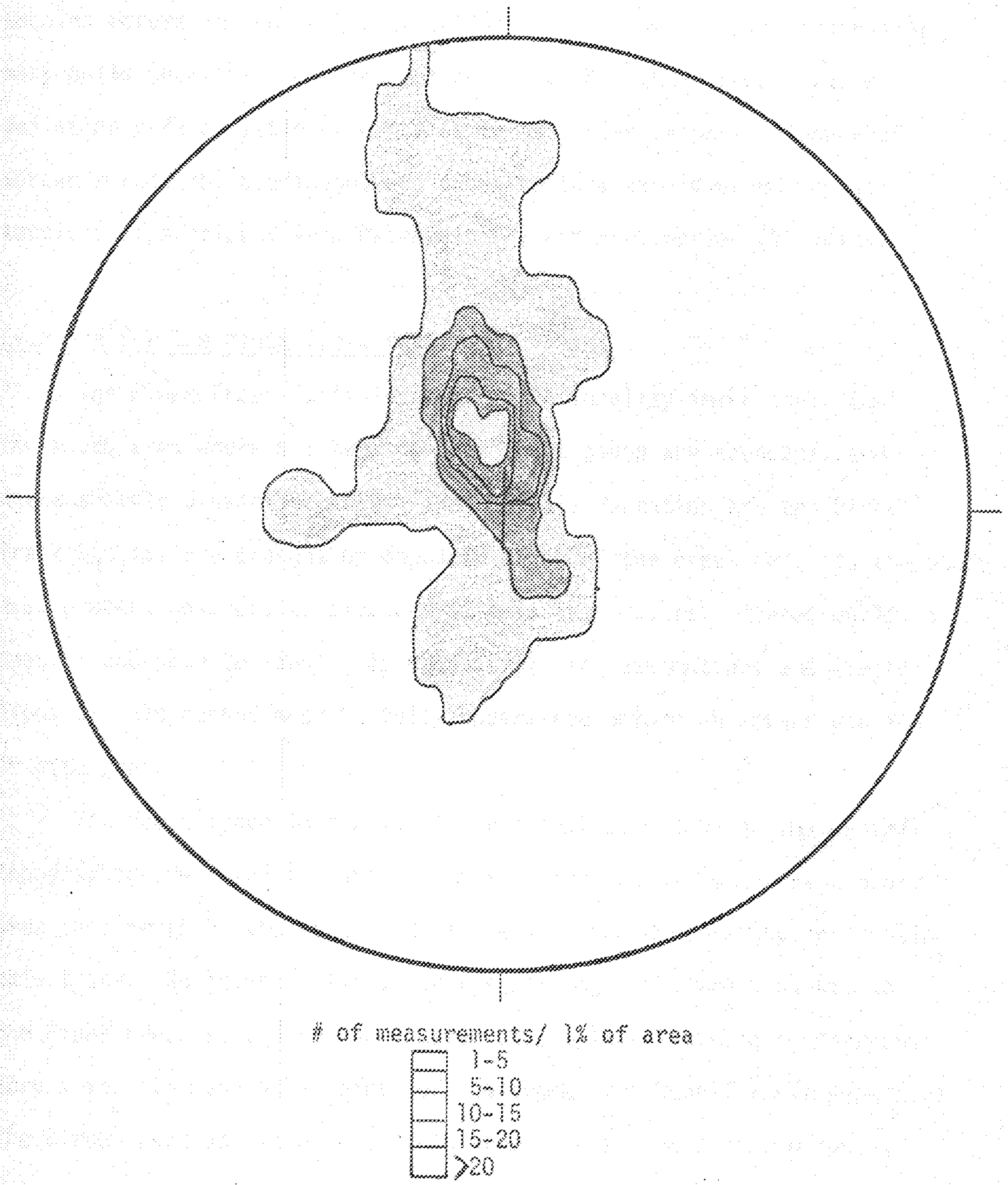

Figure 16. Equal-area net diagram of 84 poles to S_2 in the Birch Creek Schist.

pebbles occurs in one conglomerate lens in this unit. Slickensides in many units show that shearing has occurred, but their considerable variation offers little evidence as to its orientation. Evidence of mortar structure, boudinage, and augen texture was observed in thin sections of specimens from Paleozoic (?) and Precambrian (?) units.

Evidence for the Hines Creek fault

The Hines Creek fault is named for a locality immediately east of the study area where slickensides and fault gouge are abundant, and where sharply dissimilar rocks, the Cantwell Formation and the Birch Creek Schist, are present on opposite sides of the creek bed. In the study area proper, however, no evidence of this type occurs. Consequently, a special approach to mapping is necessary; the assumptions and limitations of this method must be fully understood before an interpretation is attempted.

The fault trace in the thesis area must pass through the central topographic low. Considerable talus from the foothills covers a broad area just north of the park road, increasing the uncertainty in locating this trace. No recent offsets, scarps, or sag ponds are present, so the Hines Creek strand can be located only by the lithologic contrasts across it. In many other parts of its trace, the Denali fault separates the Birch Creek Schist on the north from younger rocks on the south; nowhere in Alaska is Birch Creek Schist exposed south of the Denali fault. Therefore, in this study the approximate southern limit of the Birch Creek Schist has been mapped as the fault trace.

This trace separates the Birch Creek Schist from the Tertiary Nenana Gravel, coal-bearing group and Cantwell Formation east of the Teklanika River; west of that river, the Paleozoic (?) slate abuts the schist. Considerable difficulty is caused by the paucity of exposures immediately south of the proposed trace. In the west end of the area, the fault trace is only located to about 1/4 mile accuracy; in the vicinity of the Savage River campground, the proposed trace may be in error by as much as a mile. The concealed trace beneath the Teklanika River is purely a speculative connection across the river.

Even where outcrop data define the lithologic discontinuity rather precisely, such as between the Savage and Sanctuary Rivers, there is some doubt as to whether this boundary is the fault trace. The Tertiary coal-bearing group and Nenana Gravel lap up onto the Birch Creek Schist north of the Outer Range. It is not inconceivable that the contact on the north is also depositional, with some steepening of initial dips due to resumed uplift. If the Hines Creek fault was inactive during the time these units were being laid down, it is entirely possible that a more southerly trace lies buried beneath these poorly consolidated Tertiary rocks. Wahrhaftig (1970a) remarks that overlap and offset of these units occurs along the trace of the Hines Creek fault. His statement epitomizes the problem encountered here rather well.

No estimation of the width of the fault zone was possible. A deeply weathered red brown outcrop of Birch Creek Schist near the Savage River bridge was considered at first as possible evidence for mineralization or at least migration of waters along the fault plane. Subsequent investigations north of the range, however, disclosed similar weathering phenomena. It is more likely a result of the exhumation by erosion of an older weathered surface on the schist terrane.

The fault trace seems relatively straight except for a bend at the Teklanika River. This straightness is more a function of the ambiguities of location than of the attitude of the fault plane, although steep dips have been claimed elsewhere along the fault. The trace must curve at the Teklanika River, however; very convincing evidence would be necessary to have the fault extend straight through the Birch Creek Schist. The study area definitely does not possess enough evidence to establish the first occurrence of Birch Creek Schist south of the Denali fault. Rather, it is reasonable to run the Hines Creek fault through the more fundamental lithologic boundary, that between the schist and the Paleozoic (?) slate.

Displacement along the Hines Creek fault in the study area is unknown. Recent deposits are undisturbed, and no structures or contacts can be correlated across the fault. The occurrence of older rocks on the northern side of the trace suggest that this block has moved up relative to the southern block. Because apparent movements can be very deceiving, no judgment about the direction of net slip is made. The amount of displacement poses a similar problem. Capps (1940) states that the displacement on the fault is at least 10,000 feet, with the south side downthrown. His estimate is based on stratigraphic throw, assuming the Birch Creek Schist lies buried beneath the full stratigraphic column south of the fault. Since the relations of the Birch Creek Schist to younger units are poorly known, this conclusion may be erroneous. Aside from advocating caution in using this estimate, nothing can be added to this earlier statement on the basis of evidence from the study area.

Minor fault

One example of a minor fault was discovered. On the northern flank of Double Mountain, the exposed section of Cantwell Formation lacks its usual coarse, basal conglomerate. Of the many lithologic units in the sedimentary member, the basal conglomerate is both the most widespread and the most distinctive. The absence of this unit is interpreted as indicating a minor fault, trending approximately east-west with the north block upthrown. Further tracing of this fault is precluded by a wide lowland marsh.

INTERPRETIVE STRUCTURAL GEOLOGY

Regional stress history

When the structures previously described are subjected to dynamic analysis, one consistent stress state appears to have dominated the northeastern Mount McKinley Park area throughout much of Phanerozoic time. The stress field inferred, one of essentially north-south horizontal compression, is substantiated by the agreement of results from rocks of a variety of compositions and ages.

The features which preserve the record of this stress configuation include large-scale folds and small-scale folds in all units. The maximum principal stress was probably oriented normal to the axes of these west-trending folds. Although the formation of fracture cleavage, the strain-slip cleavage of Turner (1963), is not fully understood mechanically, the maximum principal stress is probably contained in the plane perpendicular to the strike of the cleavage. While this conclusion does not require horizontal compression exclusively, it is compatible with such a state. The Alaska Range itself, which appears to be a regional compressional feature, can also be regarded as the product of north-south compression in this area.

This stress field has caused severe dynamic metamorphism, apparently at recurrent intervals, since intensity of metamorphism increases with age in the rock units. It surely began affecting the study area as long ago as Mesozoic time since the Paleozoic (?) rocks are more strongly affected than Paleocene beds; the structure of the Birch Creek Schist suggests this stress state may have been present earlier. This configuration was dominant until at least post-Nenana Gravel time since this unit also bears its imprint. The unfolded nature of Quaternary deposits implies either a relaxation or disintegration of this stress field in Holocene time. No strain expression of the present dynamic configuration is recognized in the study area.

Hines Creek fault

Although direct evidence for the nature of the Hines Creek fault is scarce, any mechanical interpretation must be consistent with the derived regional stress pattern. Evidence for north-south compression is overwhelming; if the Hines Creek fault were in existence during any or all of this period, it must have functioned as a reverse or thrust fault. Displacement estimates of north side up are consistent with the Hines Creek fault's functioning as a reverse fault.

Strike-slip movement, which has been postulated extensively along the Denali fault, is quite difficult to reconcile with evidence from the Hines Creek fault. The abrupt bend in the fault at the Teklanika River poses a problem for the strike-slip interpretation; it may be only an apparent bend, however, if the fault trace is in reality buried under Tertiary units and located farther south than shown on Plate I. A more real difficulty is that structures in all units through the Paleocene (?) record an inferred stress field which is incompatible with strike-slip faulting. Since the Paleocene, a new stress configuration could have ushered in an episode of predominantly strike-slip movement, but again, there is no reason to suppose this from the results of this study.

Timing of tectonic events

Due to the repeated deformations in the study area and the scarcity of good datum planes, even a rudimentary tectonic history is difficult to establish. Nevertheless, a sequence of events can be inferred, along the following lines:

1) In the Precambrian and early Paleozoic, the sediments which evolved into the Birch Creek Schist were deposited. Initial deformation of these rocks prior to the deposition of the Paleozoic (?) slate is suggested by the greater structural complexity of the Birch Creek Schist.

2) Deposition of the Paleozoic (?) slate and associated rocks followed at a later but unknown time.

3) Deformation of the Paleozoic slates may coincide with synchronous intrusion of Paleozoic (?) gabbro. Structural concordance of gabbro plutons with folding trends of Paleozoic (?) slate makes relative age determination between the folding and the intruding difficult. This compressive episode may correspond to the Devonian or Pennsylvanian emergence demonstrated elsewhere in the Alaska Range. In the late Cretaceous, the culminating orogeny of the Alaska Range deformed both pre-existing units. Mesozoic strata either were not deposited locally or were destroyed by erosion.

4) Deposition of the Cantwell Formation unconformably upon older units occurred in a subsiding basin along the axis of the range. Sedimentation continued throughout the Paleocene, with extrusive volcanism beginning in late Paleocene to early Eocene. Post-Paleocene but pre-Miocene strong regional compression folded the Cantwell Formation and

increased the intensity of deformation in the Precambrian and Paleozoic (?) rocks. Tertiary intrusions were emplaced at this time.

5) During Oligocene and Miocene time the Tertiary coal-bearing group formed as a piedmont deposit.

6) In the late Miocene and early Pliocene came the uplift which produced the present Alaska Range. This uplift is recorded by folds in the coal-bearing group and by the presence of the Pliocene (?) Nenana Gravel. The Nenana Gravel was eventulally caught up in the orogeny which produced it, and is also folded.

7) Deformation ceased 1.5 - 3.0 million years ago since glacial deposits have not been disturbed.

The regional north-south compressional field existed at least during events 3 through 5, and possibly during 6. To date the time of relaxation of this stress state, a decision must be made as to the origin of folds in the Tertiary coal-bearing group and Nenana Gravel. If these are compressive folds, the pre-existing compressive state was still present. If the folds are merely flexures resulting from block uplifts, a reorientation of principal stress axes could have occurred. The poor exposures of the folds in question precludes a definite judgment of stress history on this basis.

It is conceivable that the Hines Creek fault could have been active, intermittently or continuously, throughout this period of north-south compression; the fact that no rock units can be designated as definitely pre-fault hinders estimation of the time of its inception.

Throughout this time it probably functioned, if active, as a reverse fault; any other mechanical classification is feasible only in the post-Paleocene or possibly post-Pliocene.

Regional implications

The intent of this work has not been to generalize to the whole of Alaska on the basis of 250 square miles. Any attempt at global tectonic synthesis based on these limited findings is totally unwarranted. This study does, however, allow some insight into the feasibility of certain models; within this framework, a few modest extrapolations can be offered.

A paradigm for plate interactions is proposed for California by Atwater (1970). She accounts for the change from oblique subduction to strike-slip faulting by subducting the spreading ridge itself. Grow and Atwater (1970) apply a similar model to the northeastern Pacific Ocean and the Aleutian trench. The tectonic pattern for Alaska changes from north-south compressional, when subduction is occurring, to strike-slip faulting, after the ancient spreading ridge is consumed. This time estimate for this change is middle to late Tertiary.

In the Alaska Range, Hickman (1971) has demonstrated Recent strike-slip movement beginning in approximately mid-Tertiary time on the McKinley strand. The McKinley strand has been cited as a more efficient, mechanical "short circuit" of the older Hines Creek fault. Thus, the McKinley strand probably cut off the longer Hines Creek trace as the nature of plate interactions changed, and strike-slip faulting became the dominant tectonic expression. By similar reasoning, the reverse nature of the

Hines Creek fault preserves a record of the period before subduction of the ridge, when north-south compression resulted from plate interactions.

The true nature of the Hines Creek fault is probably much more complicated. Though it is bypassed by the McKinley strand, microseismic work (Boucher and others, 1968) suggests that the Hines Creek fault is still quite active. More detailed work is needed along the Hines Creek fault and especially at the junctions between the McKinley and Hines Creek strand, to clarify the relation of these two faults.

CONCLUSIONS

As a result of the study of the Hines Creek fault in northeastern Mount McKinley National Park, the following generalizations can be made.

1) The trace of the Hines Creek fault may not be as straight as originally thought.

2) The stress field in northeastern Mount McKinley National Park has been dominantly one of lateral compession with the maximum principal stress axis oriented approximately north-south.

3) Throughout much of geologic time, probably until the late Miocene to early Pliocene, the Hines Creek fault must have acted as a reverse fault.

4) No evidence of strike-slip movement along the fault was discovered.

5) The Hines Creek fault is currently active microseismically, but no geologic evidence was found for movements on this strand during Holocene time.

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APPENDIX 1. SPECIMENS REFERRED TO IN TEXT

Univ. of Wis. Number — Field Notebook Number

Radiometric age dating samples

UW 1562/1 — T20

NW/4 NW/4 SW/4 Sec. 25, T. 14 S., R. 9 W. in Healy C-5 quad., Alaska
Paleozoic (?) gabbro

UW 1562/2 — X10

SW/4 NW/4 SW/4 Sec. 28, T. 14 S., R. 11 W. in Healy C-6 quad., Alaska
Paleozoic (?) gabbro

UW 1562/3 — U2

SW/4 NW/4 SE/4 Sec. 48, T. 15 S., R. 11 W. in Healy C-6 quad., Alaska
Cantwell Formation (upper volcanic member)

UW 1562/4 — W6

NW/4 SE/4 NW/4 Sec. 22, T. 15 S., R. 10 W. in Healy C-5 quad., Alaska
Cantwell Formation (upper volcanic member)

Chemical analysis samples

UW 1562/5 — T2

NW/4 NW/4 SW/4 Sec. 25, T. 14 S., R. 9 W. in Healy C-5 quad., Alaska
Paleozoic (?) gabbro

UW 1562/6 — W5

NW/4 SE/4 NW/4 Sec. 22, T. 15 S., R. 10 W. in Healy C-5 quad., Alaska
Cantwell Formation (upper volcanic member)

APPENDIX 2. POTASSIUM-ARGON DETERMINATION DATA

Analytical work done by and samples on file with

Geochron Laboratories
24 Blackstone Street
Cambridge, Mass. 02139

$\lambda_\beta = 4.72 \times 10^{-10}$/year

$\lambda_e = 0.585 \times 10^{-10}$/year

$K^{40}/K = 1.22 \times 10^{-4}$ g/g

$$\text{Age} = \frac{1}{\lambda_e + \lambda_\beta} \ln \left[\frac{\lambda_\beta + \lambda_e}{\lambda_e} \times \frac{Ar^{40*}}{K^{40}} + 1 \right]$$

See Appendix 1 for geographic location and stratigraphic position of specimens.

1) Specimen UW 1562/1

Analysis to define age of pluton and by inference the sedimentary rocks it intrudes.

Pyroxene concentrate analysis of pyroxene gabbro (Ps)

Ave. Ar^{40*}, ppm = .002876

K^{40}, ppm = .124

Ar^{40*}/K^{40} = .02311

Age = 359 ± 44 million years

2) Specimen UW 1562/2

Analysis done to define age of pluton and by inference the sedimentary rocks it intrudes.

Whole rock analysis of altered gabbro (Ps)

Ave. Ar^{40*}, ppm = .003928

K^{40}, ppm = .186

Ar^{40*}/K^{40} = .02104

Age = 329 ± 30 million years

3) Specimen UW 1562/3

Analysis done to define age of the volcanic member of the Cantwell Formation.

Whole rock analysis of basalt (Tv) from Double Mountain

Ave. Ar^{40*}, ppm = .008441

K^{40}, ppm = 2.581

Ar^{40*}/K^{40} = .003270

Age = 55.1 ± 2.3 million years

4) Specimen UW 1562/4

Analysis to define age of the volcanic member of the Cantwell Formation.

Whole rock analysis of basalt (Tv) from Igloo Mountain

Ave. Ar^{40*}, ppm = .005932

K^{40}, ppm = 1.682

Ar^{40*}/K^{40} = .003525

Age = 59.3 ± 2.7 million years

APPENDIX 3. CHEMICAL ANALYSIS

Analyses were done of fused whole rock samples using University of Wisconsin electron microprobe facilities. The actual probe work was done by Mike Brauner with standards of known composition supplied by Bob Jenkins.

After being crushed, sieved, and sorted, specimens were ball milled to a fine powder. This powder was mixed with a flux and fused twice to assure homogeneity of the resultant glass. The glasses obtained were cast in plastic, polished, and coated for use in the microprobe.

Specimens selected for analysis include all rocks submitted for radiometric age determination (see Appendix 2) as well as UW 1562/5, Paleozoic (?) gabbro, and UW 1562/6, a pyroclastic rock from the upper volcanic member of the Cantwell Formation.

Results of the analyses are tabulated. Deviations from 100 percent total can be attributed to several factors. Most analyses, except UW 1562/5, are reasonably good

1) Not all oxides were analyzed for.

2) Carbon analyses were not done. One or two percent are added due to presence of significant calcite or graphite.

3) Analyses were done with only one standard. Errors of several percent occur when composition of specimen being analyzed is not close in composition to the standard used.

4) Experimental error.

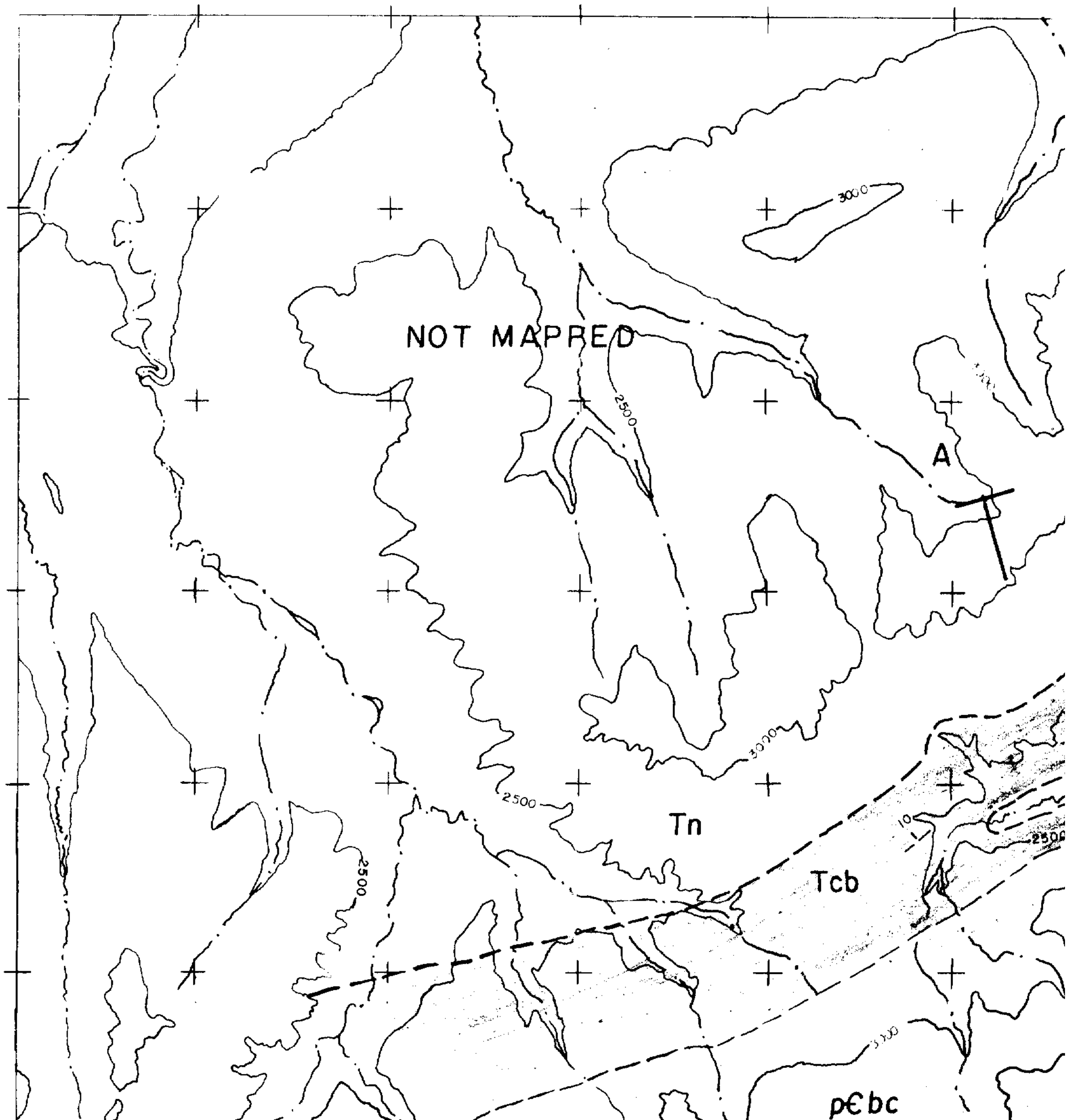
	UW1562/1	UW1562/2	UW1562/3	UW1562/4	UW1562/5	UW1562/6
FeO	10.50	9.91	11.42	9.40	13.25	4.70
CaO	10.87	10.94	6.11	9.14	8.25	1.54
Na_2O	2.42	3.00	3.17	2.95	3.74	3.06
SiO_2	40.11	51.65	48.43	47.92	45.56	65.30
K_2O	.49	.21	2.13	1.52	.53	4.69
MgO	4.38	5.98	2.23	2.18	5.61	.32
TiO_2	1.63	1.29	2.46	1.76	1.89	.28
MnO	.17	.12	.21	.11	.20	.11
Al_2O_3	14.53	17.46	16.13	17.09	16.03	14.41
TOTAL	85.10	100.56	92.29	92.07	95.06	94.91

Campbell Craddock

APPROVED: Professor of Geology

DATE: June 2, 1972

G



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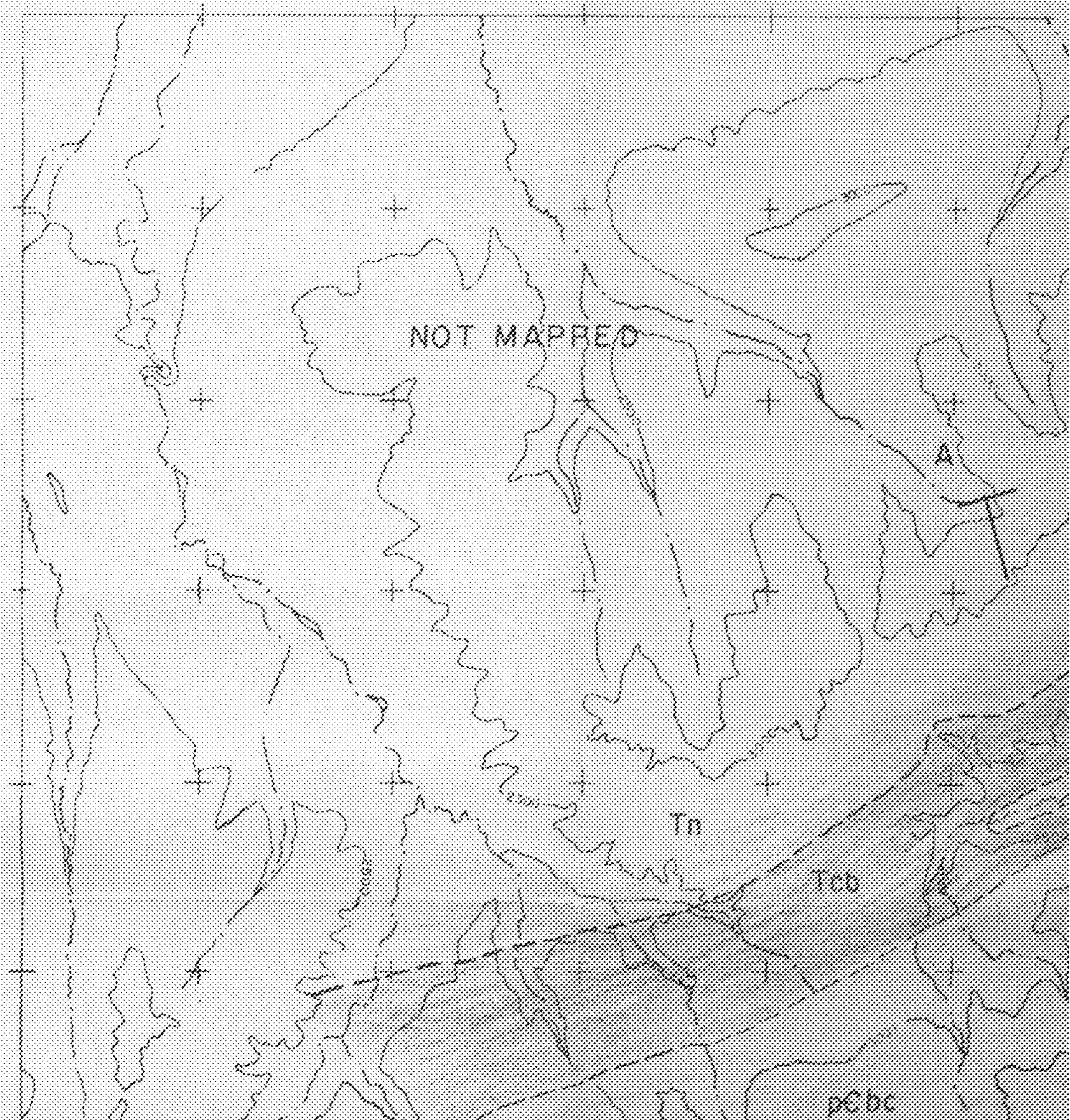
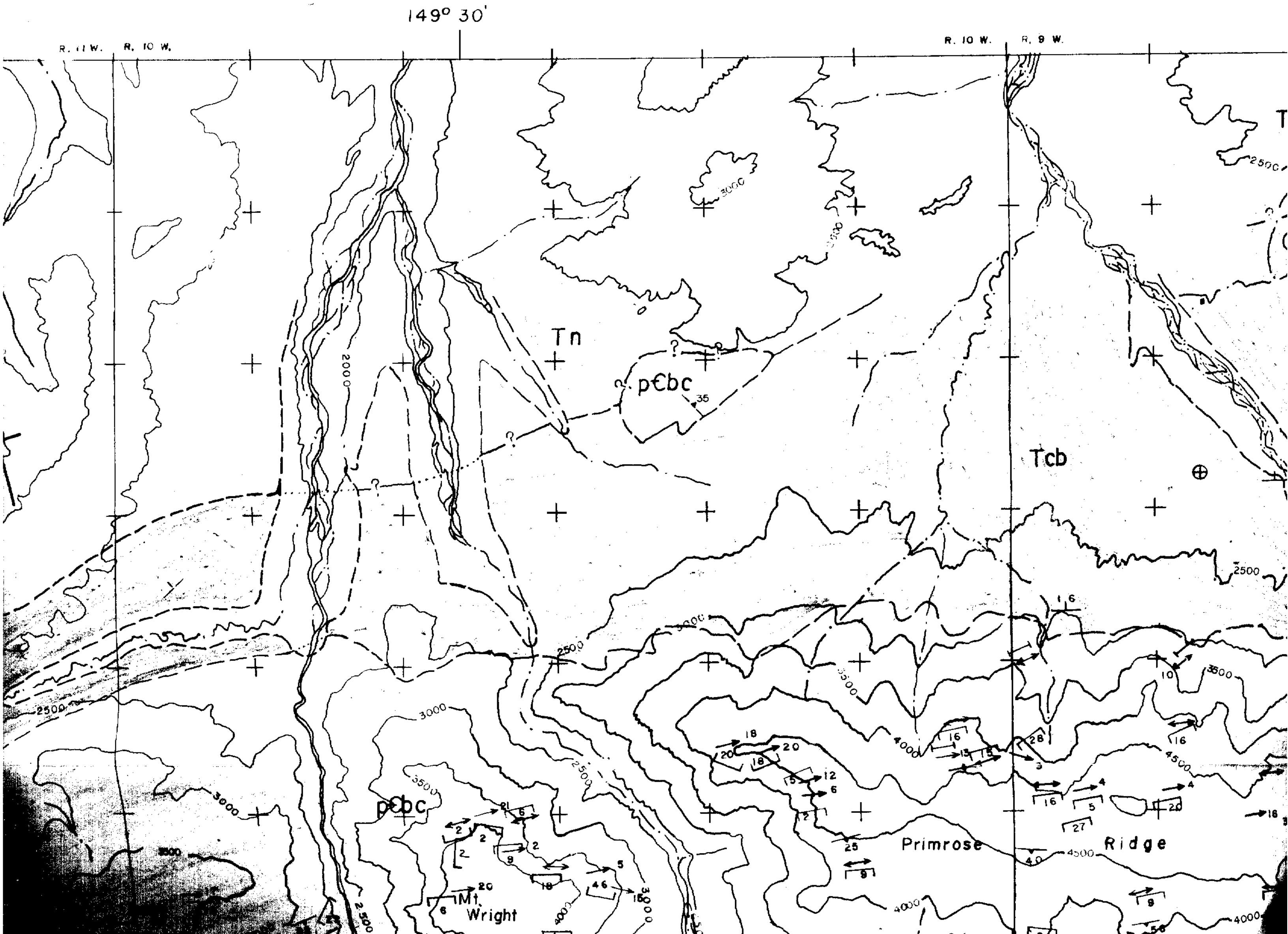
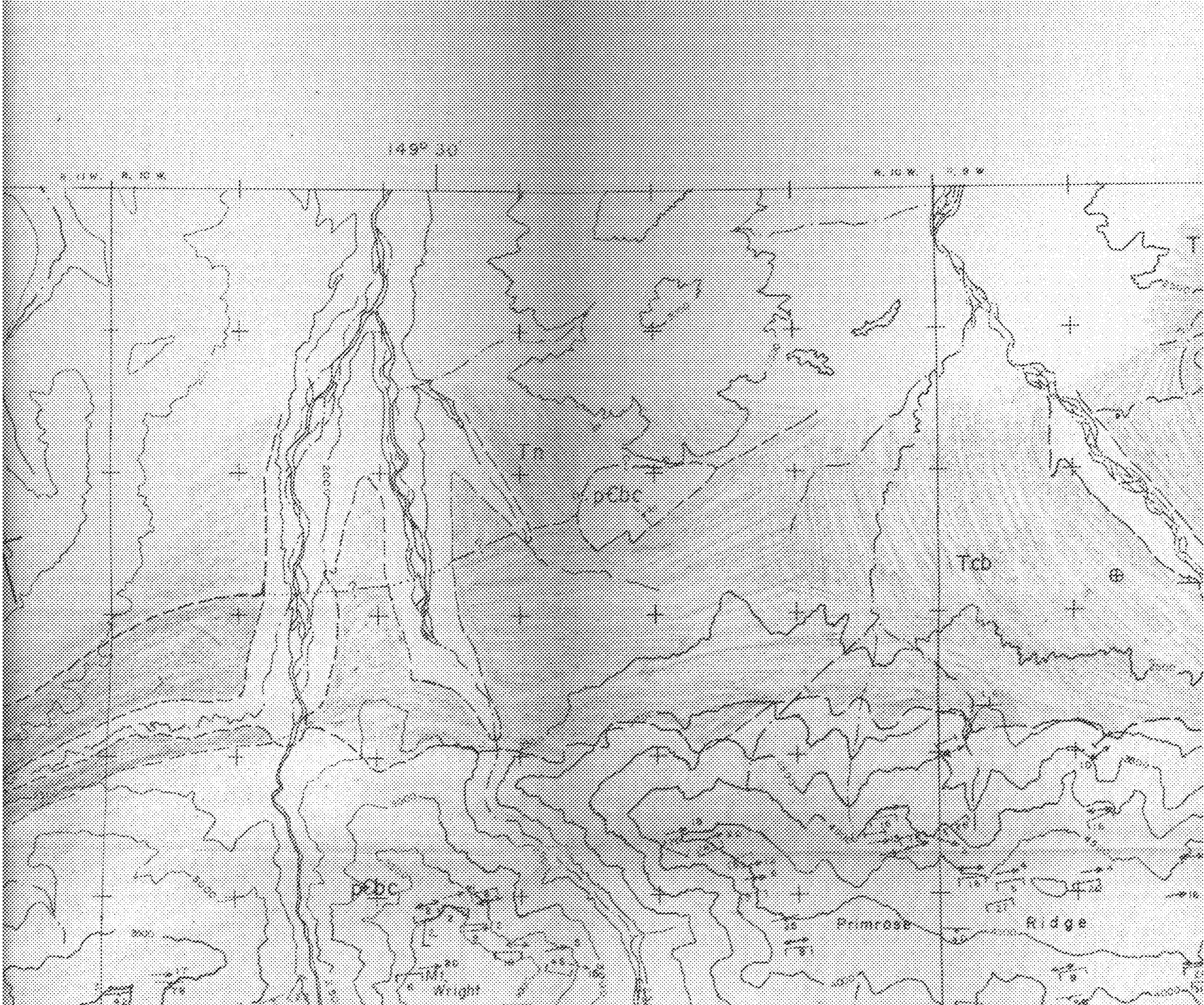


GEOLOGIC MAP OF NORTHEASTE



GEOLOGIC MAP OF NORTHEASTE



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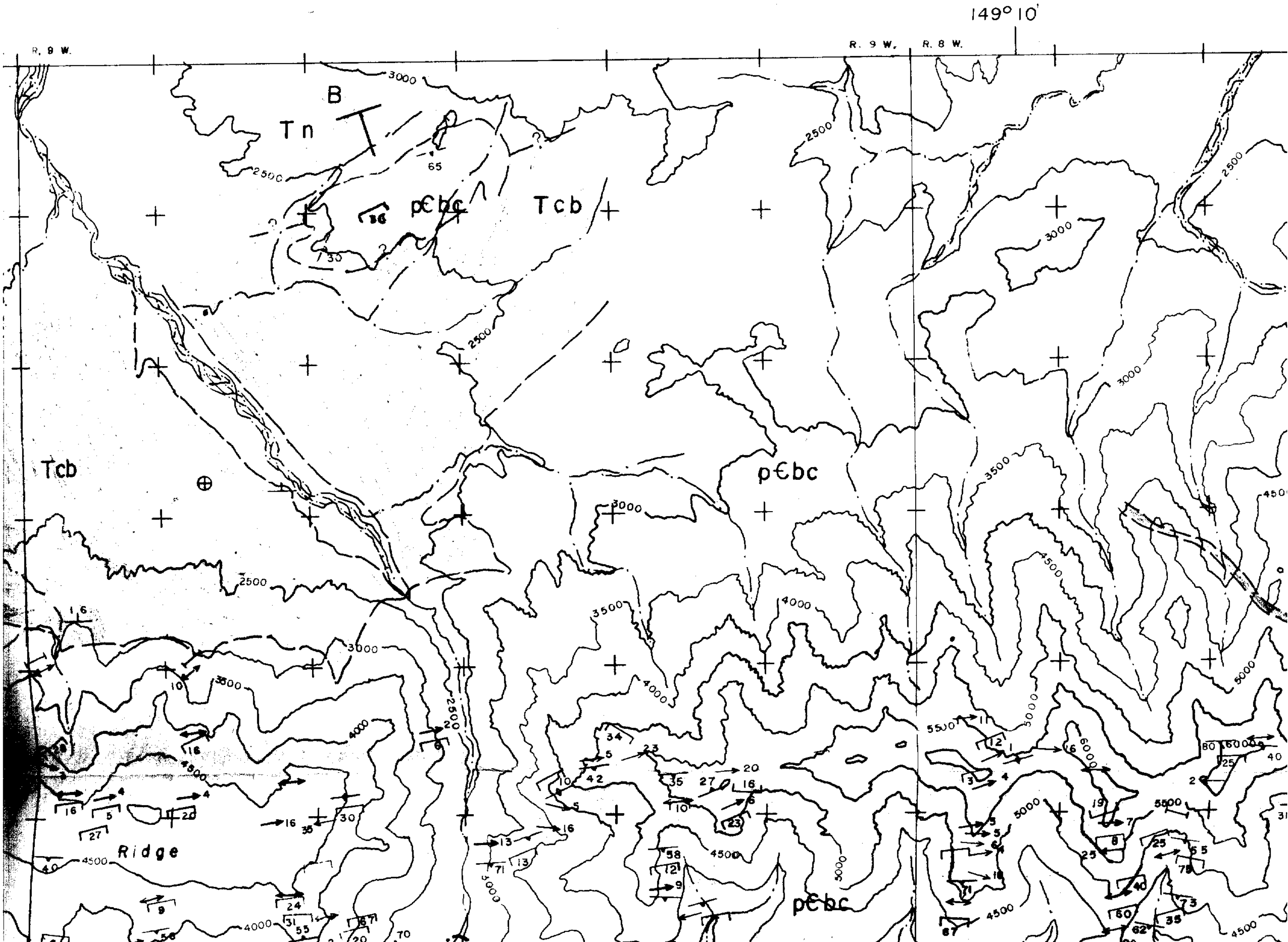

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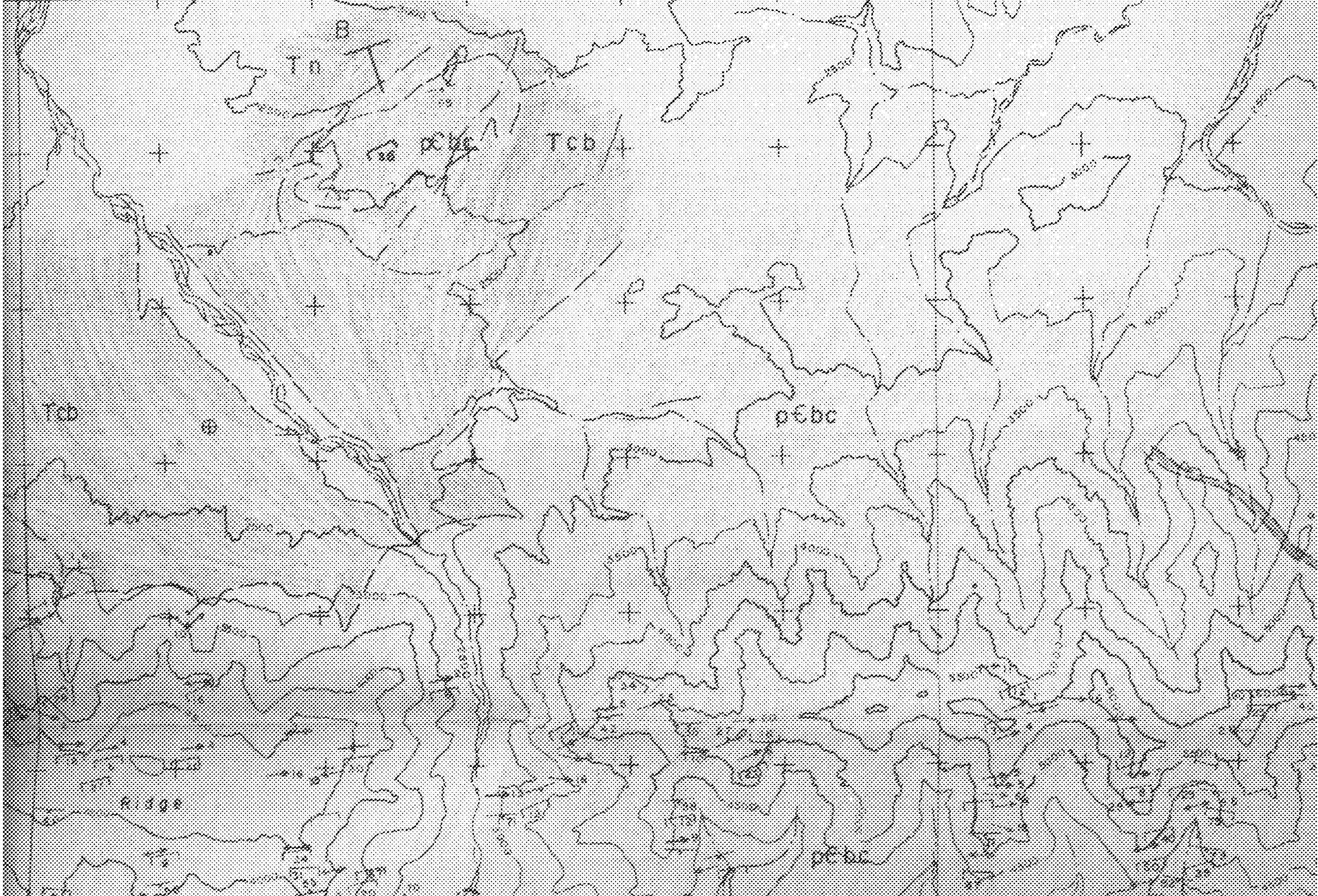
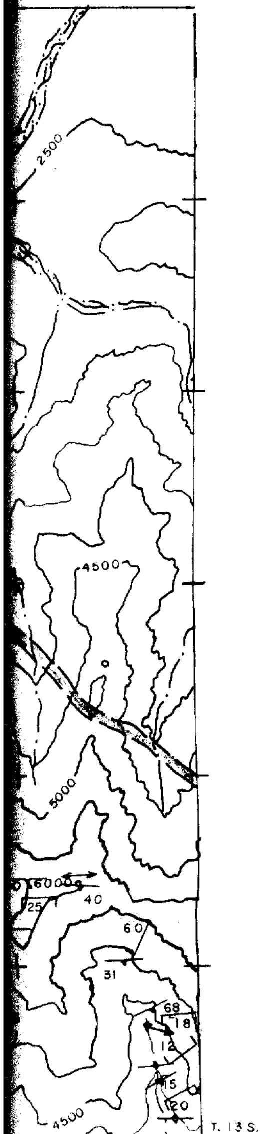


IONAL PARK P



EXPLANATION

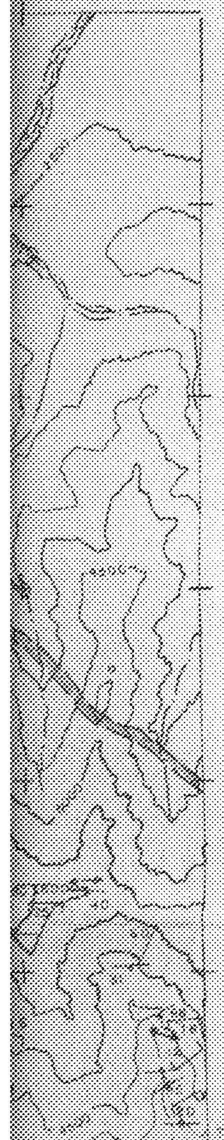
SEDIMENTARY AND VOLCANIC R

QUATERNARY	Qs	Glacial, alluvial, colluvial, a
TERTIARY		
PLIOCENE (?)	Tn	Nenana Gravel, poorly indu
OLIGOCENE to MIOCENE	Tc	Coal-bearing group, poorly
PALEOCENE	Tv/Tc	Cantwell Formation; *Tv, main* sandstone, and argillite
PALEOZOIC (?)	[illegible]	**Metasedimentary** rocks, main *conglomerate*
PRECAMBRIAN (?)	p€bc	Birch Creek Schist, *quartz-se*

IGNEOUS ROCKS

IONAL PARK

P



EXPLANATION

SEDIMENTARY AND VOLCANIC R

QUATERNARY	Qs	Glacial, alluvial, colluvial, a
TERTIARY		
PLIOCENE (?)	Tn	Nenana Gravel, poorly indu
OLIGOCENE to MIOCENE	Tcb	Coal-bearing group, poorly
PALEOCENE	Tv/Tc	Cantwell Formation; Tv, main sandstone, and argillite
PALEOZOIC (?)	Pz	Metasedimentary rocks, main conglomerate
PRECAMBRIAN (?)	pCbc	Birch Creek Schist, quartz-se

IGNEOUS ROCKS

Plate I

EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

Qs	Glacial, alluvial, colluvial, and terrace deposits
Tn	Nenana Gravel, poorly indurated sandstone and conglomerate
Tc[illegible]	Coal-bearing group, poorly indurated sandstone, claystone, conglomerate and coal
Tv/Tc	Cantwell Formation; Tv, mainly volcaic flows; lower member, Tc, coarse conglomerate, sandstone, and argillite
[illegible]	Metasedimentary rocks, mainly slate, with sandstone, chert, limestone, phyllite, and conglomerate
p€bc	Birch Creek Schist, quartz-sericite schist with quartzite, phyllite, and marble

IGNEOUS ROCKS

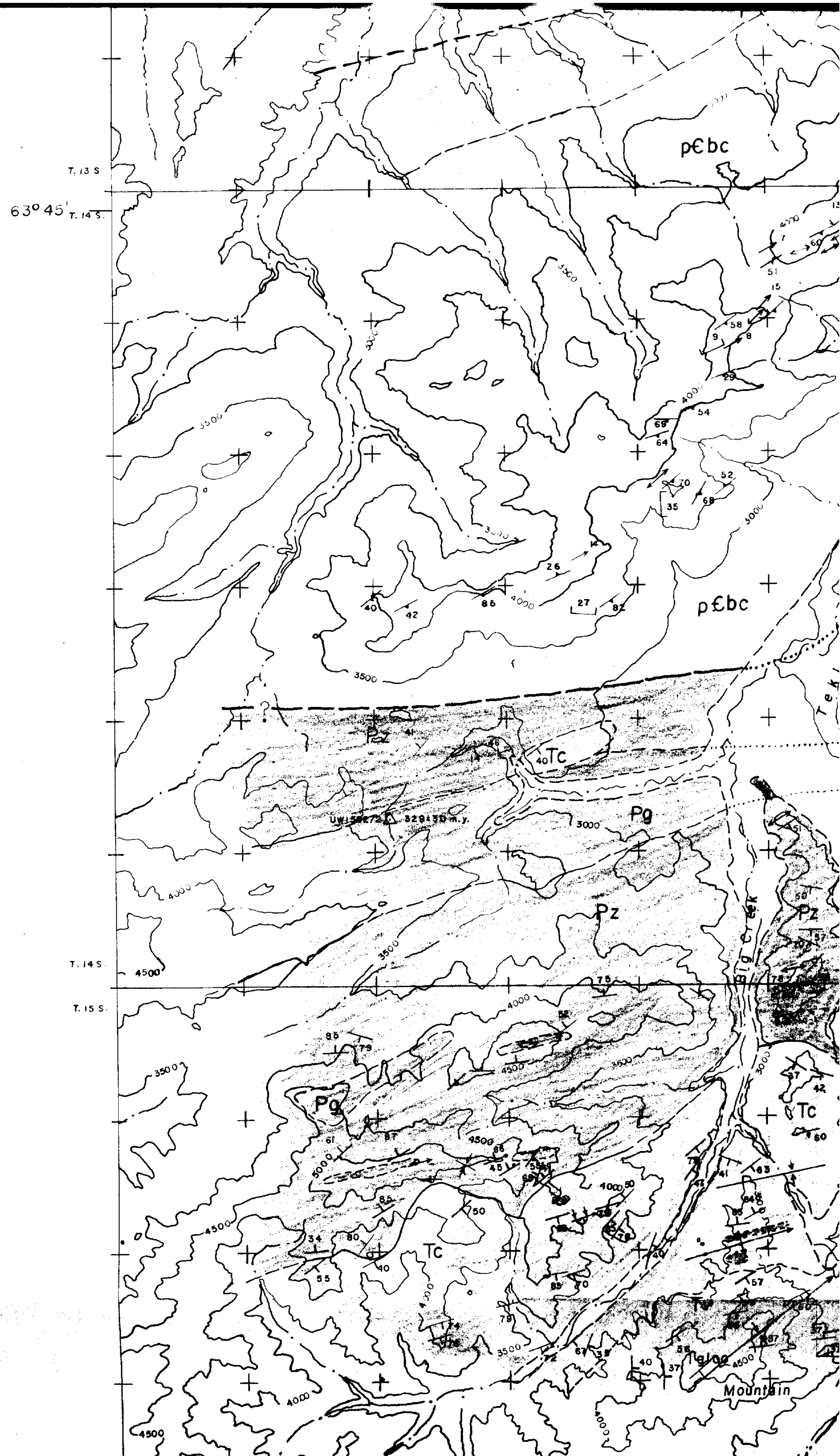
Plate I

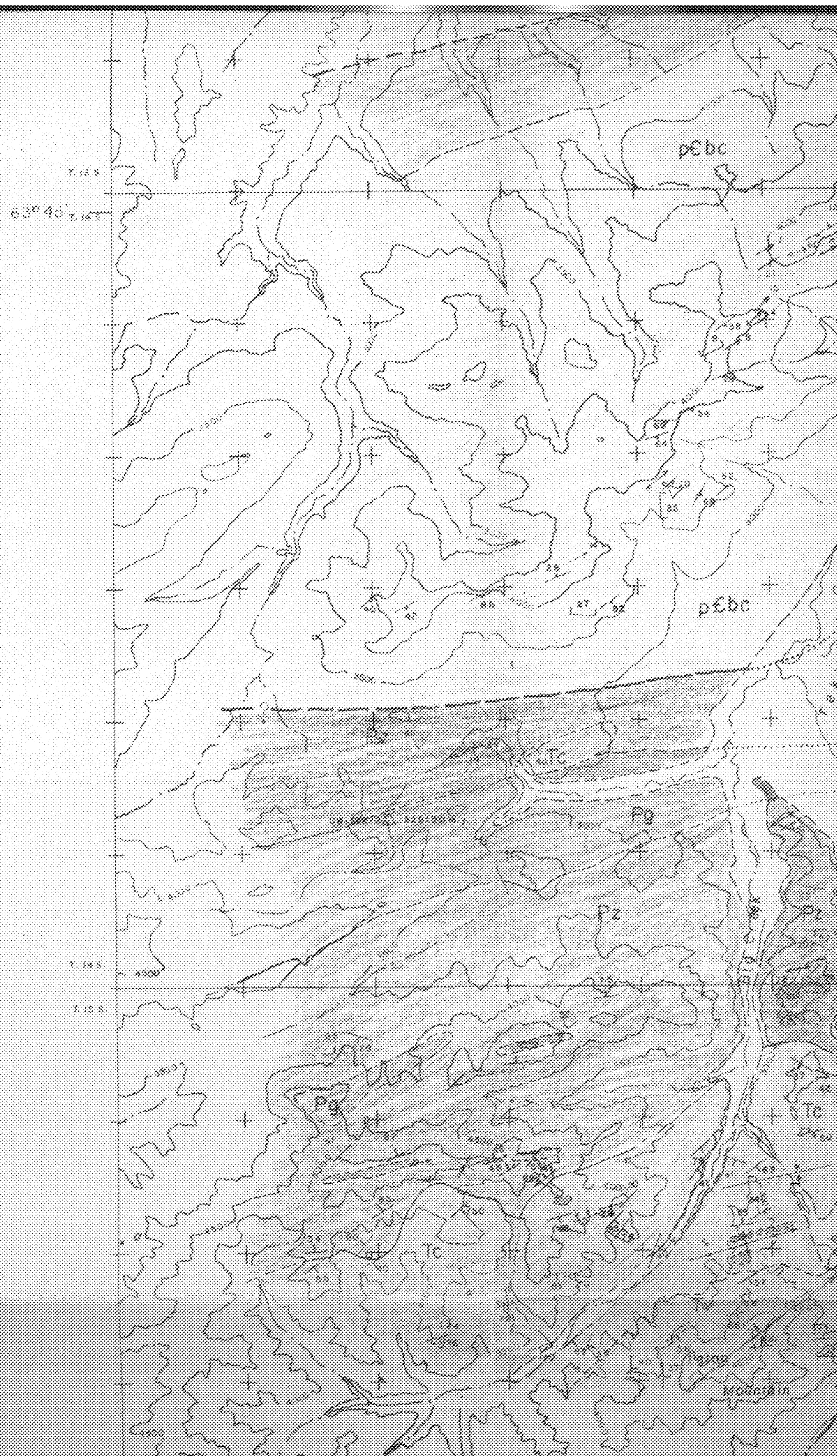
EXPLANATION

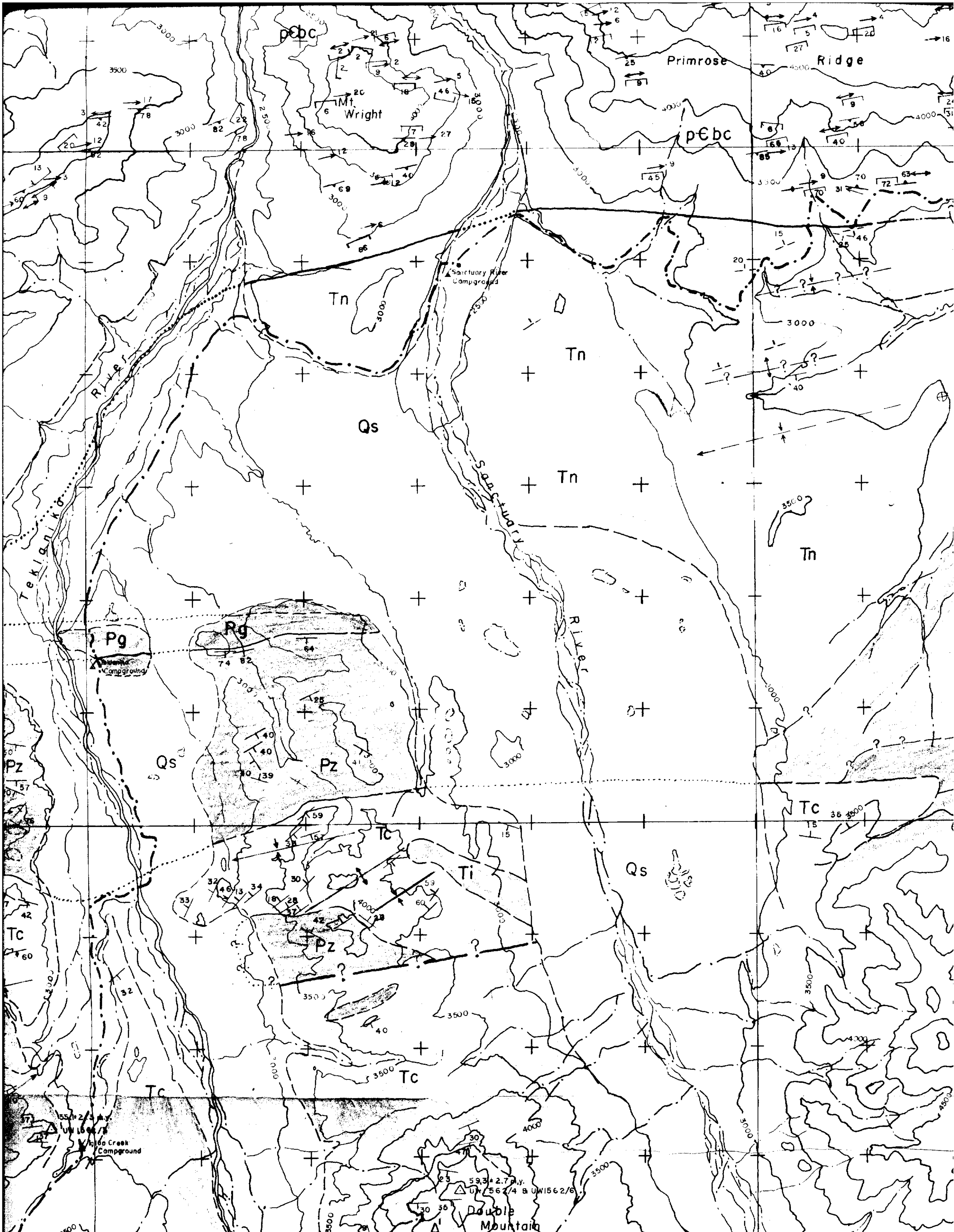
SEDIMENTARY AND VOLCANIC ROCKS

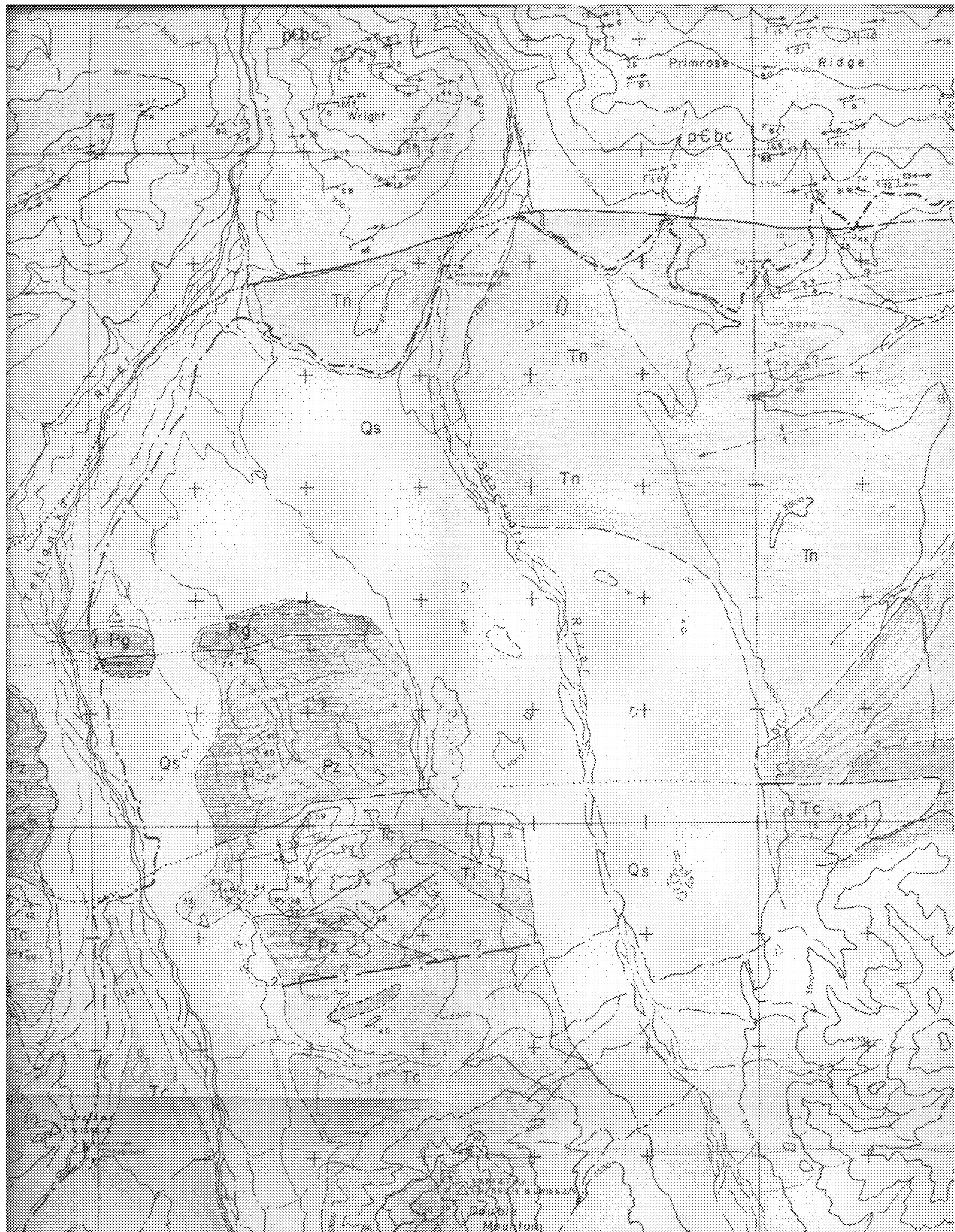
Qs	Glacial, alluvial, colluvial, and terrace deposits
Tn	Nenana Gravel, poorly indurated sandstone and conglomerate
Tcb	Coal-bearing group, poorly indurated sandstone, claystone, conglomerate and coal
Tv/Tc	Cantwell Formation, Tv, mainly volcanic flows; lower member, Tc, coarse conglomerate, sandstone, and argillite
Pz	Metasedimentary rocks, mainly slate, with sandstone, chert, limestone, phyllite, and conglomerate
pCbc	Birch Creek Schist, quartz-sericite schist with quartzite, phyllite, and marble

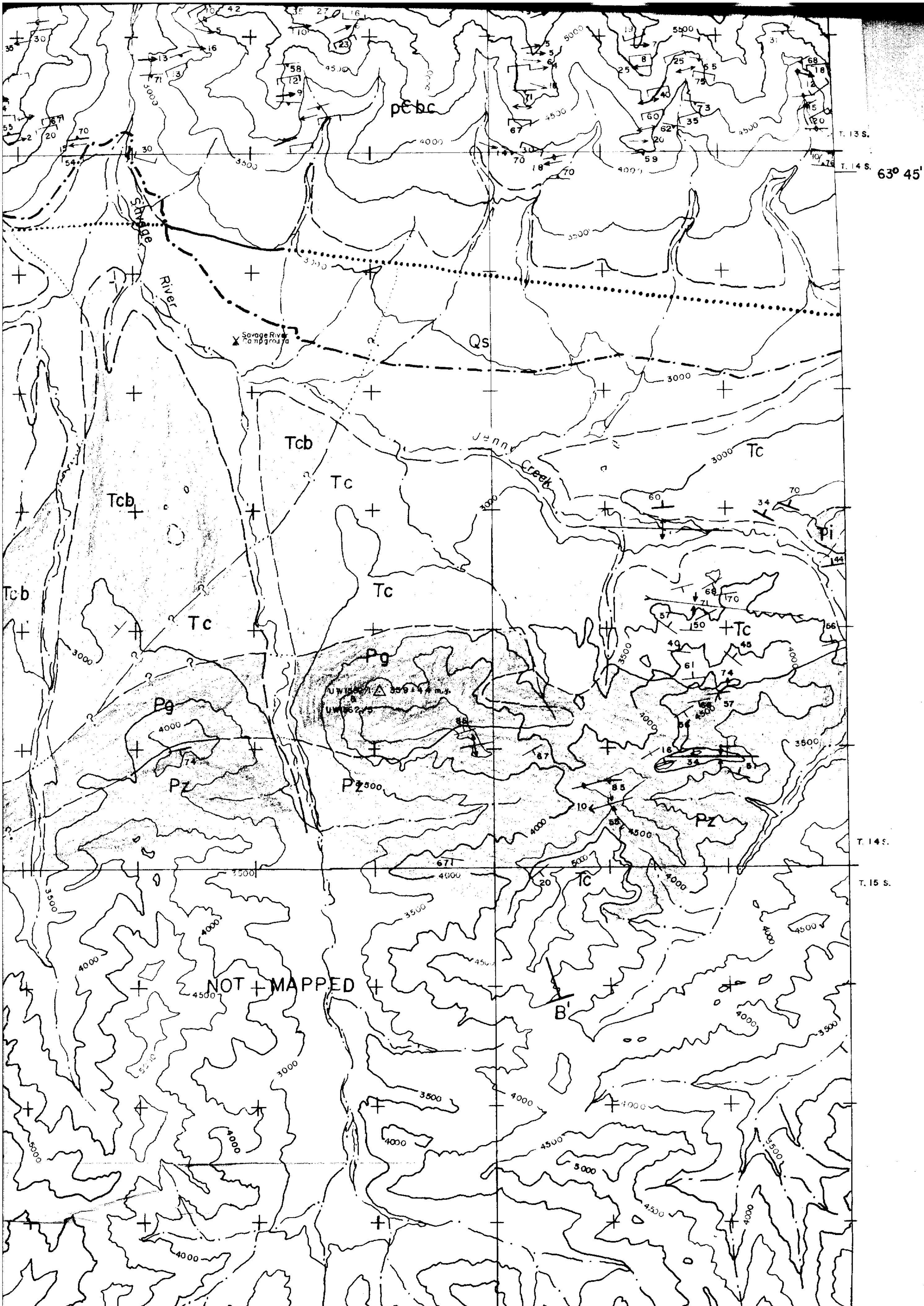
IGNEOUS ROCKS


T. 13 S.
63° 45'
T. 14 S.
T. 14 S.
T. 15 S.
pЄbc
pЄbc
Pz
Pz
Pz
Tc
Tc
Tc
Pg
Pg
UW15272 Δ 329±30 m.y.
Big Creek
Igloo
Mountain
Tek
3000
3500
4000
4500
?


T.13 S.
63°45'
T.14 S.
pCbc
p€bc
Pg
Tc
Pz
Pg
Pz
T.14 S.
T.15 S.
Pg
Tc
Tc
Mountain


pЄbc
Mt. Wright
Primrose Ridge
pЄbc
Tn
Sanctuary River Campground
Tn
Qs
Tn
Tn
Teklanika River
Sanctuary River
Pg
Pg
Campground
Pz
Qs
Pz
Pz
Tc
Tc
Ti
Qs
Tc
Pz
Tc
Tc
55.1±2.3 m.y.
UW1562/8
Igloo Creek Campground
59.3±2.7 m.y.
UW1562/4 & UW1562/6
Double Mountain
A'
3000
3500
4000
4500


pЄbc
Mt Wright
Primrose
Ridge
pЄbc
Tn
Tn
Qs
Tn
Tn
Teklanika River
Sanctuary
River
Pg
Pg
Qs
Pz
Tc
Tc
Ti
Qs
Pz
Pz
Tc
Tc
Tc
Double
Mountain



PR

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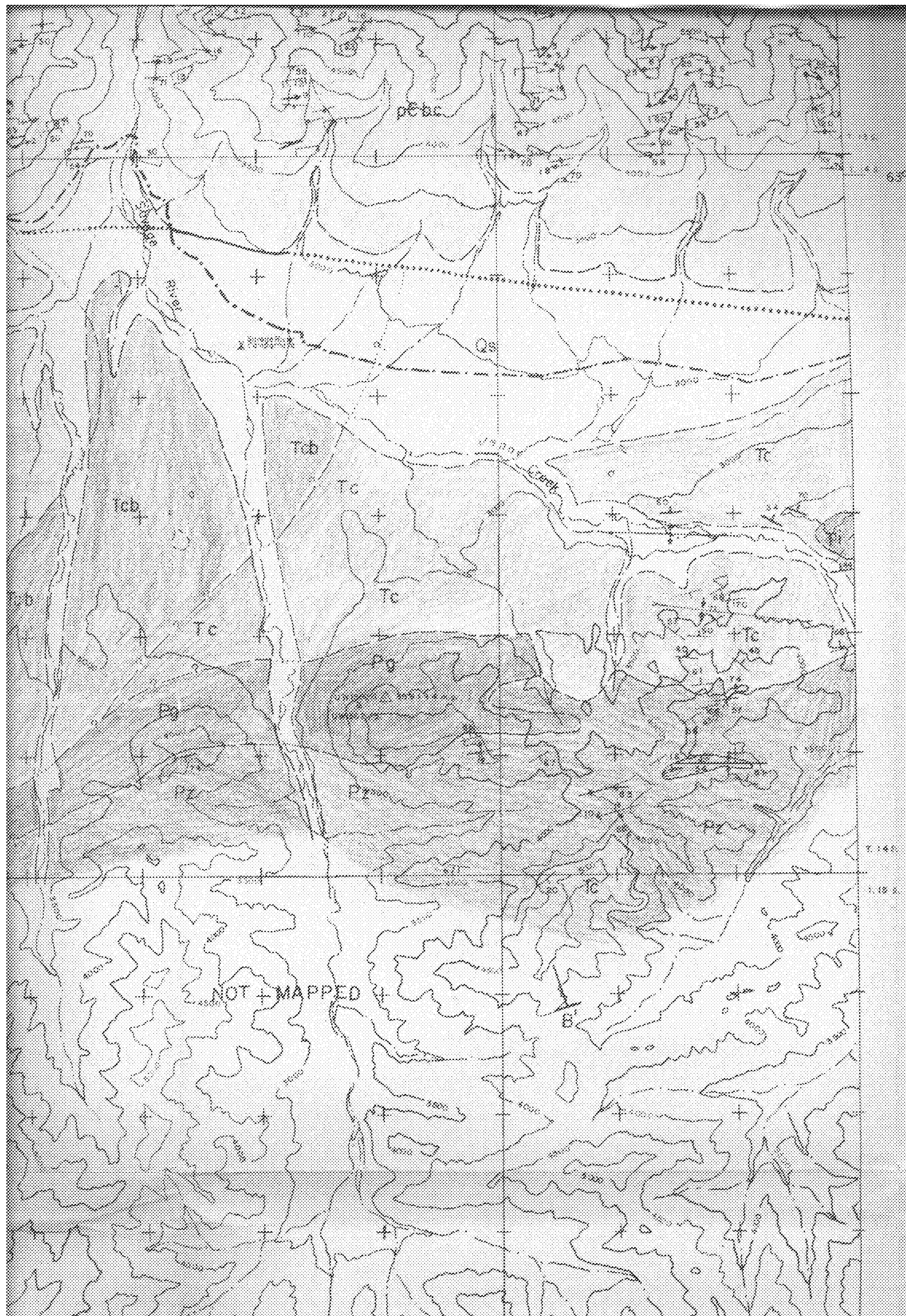

PR

LO

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PRECAMBRIAN (?)	p€bc	Birch Creek Schist, quartz-sericite schist with quartzite, phyllite, and

IGNEOUS ROCKS

LOWER TERTIARY	Ti	Mafic to intermediate intrusives
PALEOZOIC (?)	Pg	Gabbro

SYMBOLS

Contact, showing dip, dashed where approximately located or indefinite, dotted where concealed, queried where doubtful

10 — — ? — ? — · ? · ? · · · · ·

Bearing and plunge of minor fold axis

→5 ↔

inclined horizontal

Strike and dip of bedding

67 ⊥ ✛ ⊕ 85

inclined vertical horizontal overturned

12

estimated from topography

Strike and dip of fracture cleavage

7

inclined vertical

eam

ke

Fault, dashed where approximately located or inde
where concealed, queried where doubtful (U, upthrown, D

— — — ? — ? — · · · · · · · ·

Bearing and plunge of major fold axis, dashed where
located

20

syncline anticline overturned syncl

Strike and dip of foliation (S_1)

78 50

inclined vertical estimated or approximate

Chemical analysis or age dating site, and [illegible]

△ [illegible]

Topographic contours

3000

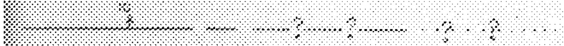
PRECAMBRIAN(?)	pCbc	Birch Creek Schist, quartz-sericite schist with quartzite, phyllite, and

IGNEOUS ROCKS

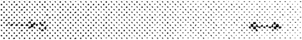
LOWER TERTIARY	Ti	Mafic to intermediate intrusives
PALEOZOIC(?)	Pg	Gabbro

SYMBOLS

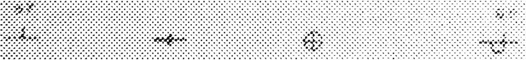
Contact, showing dip, dashed where approximately located or indefinite, dotted where concealed, queried where doubtful

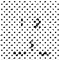


Bearing and plunge of minor fold axis

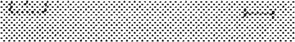

inclined horizontal

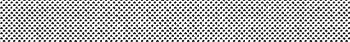
Strike and dip of bedding


inclined vertical horizontal overturned


estimated from topography

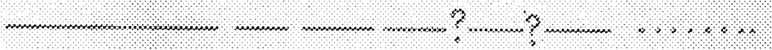
Strike and dip of fracture cleavage


inclined vertical

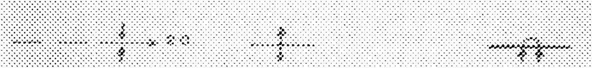
Stream 

Lake 

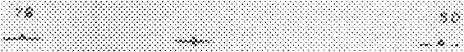
Fault, dashed where approximately located or inde where concealed, queried where doubtful (U, upthrown, D



Bearing and plunge of major fold axis, dashed where located


syncline anticline overturned syncl

Strike and dip of foliation (S_1)


inclined vertical estimated or approximate

Chemical analysis or age dating site, age in millions of

Topographic contours

pЄbc Birch Creek Schist, quartz-sericite schist with quartzite, phyllite, and marble

IGNEOUS ROCKS

Ti Mafic to intermediate intrusives

Pg Gabbro

SYMBOLS

e approximately
concealed, queried

Fault, dashed where approximately located or indefinite, dotted where concealed, queried where doubtful (U, upthrown, D, downthrown)

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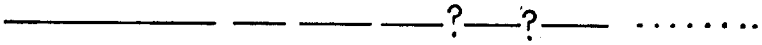


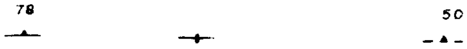
xis

Bearing and plunge of major fold axis, dashed where approximately located

syncline anticline overturned syncline

erturned

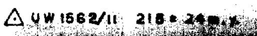
Strike and dip of foliation (S_1)



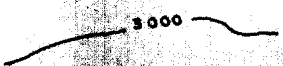
inclined vertical estimated or approximate

age

Chemical analysis or age dating site, age in millions of years



Topographic contours



e approximately
oncealed, queried

e

xis

erturned

age

pCbc Birch Creek Schist, quartz-sericite schist with quartzite, phyllite, and marble

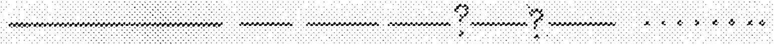
IGNEOUS ROCKS

Ti Mafic to intermediate intrusives

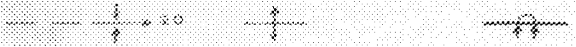
Pg Gabbro

SYMBOLS

Fault, dashed where approximately located or indefinite, dotted where concealed, queried where doubtful (U, upthrown, D, downthrown)

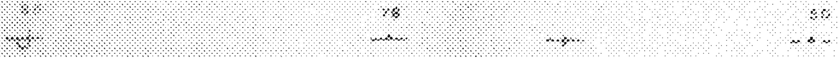


Bearing and plunge of major fold axis, dashed where approximately located



syncline anticline overturned syncline

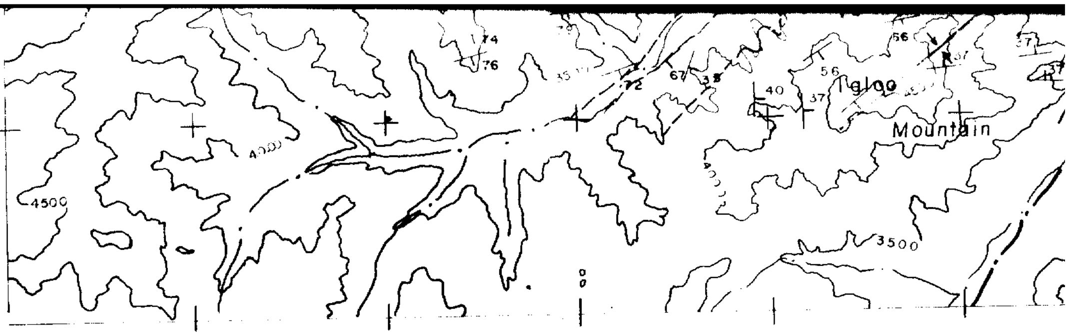
Strike and dip of foliation (S_1)



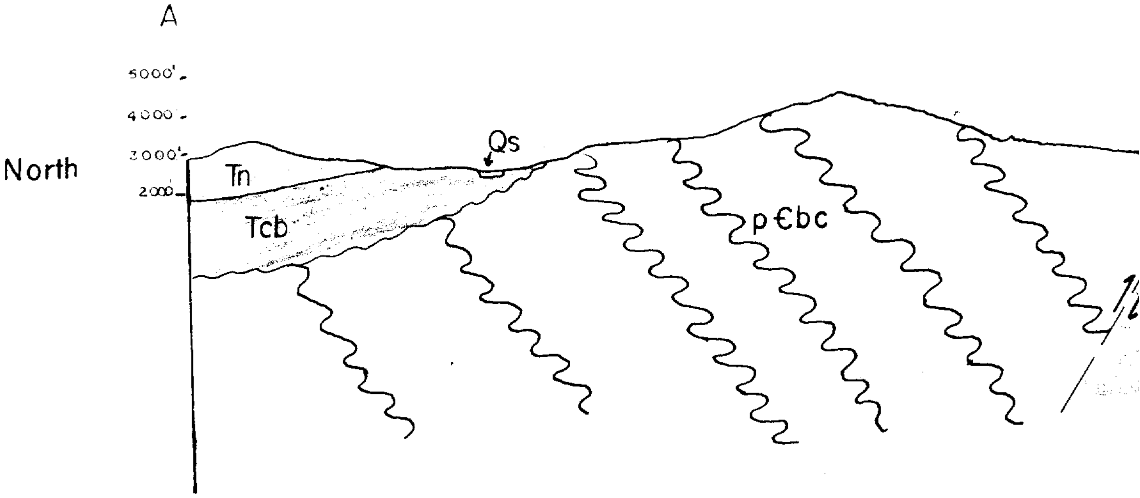
erturned inclined vertical estimated or approximate

Chemical analysis or age dating site, age in millions of years

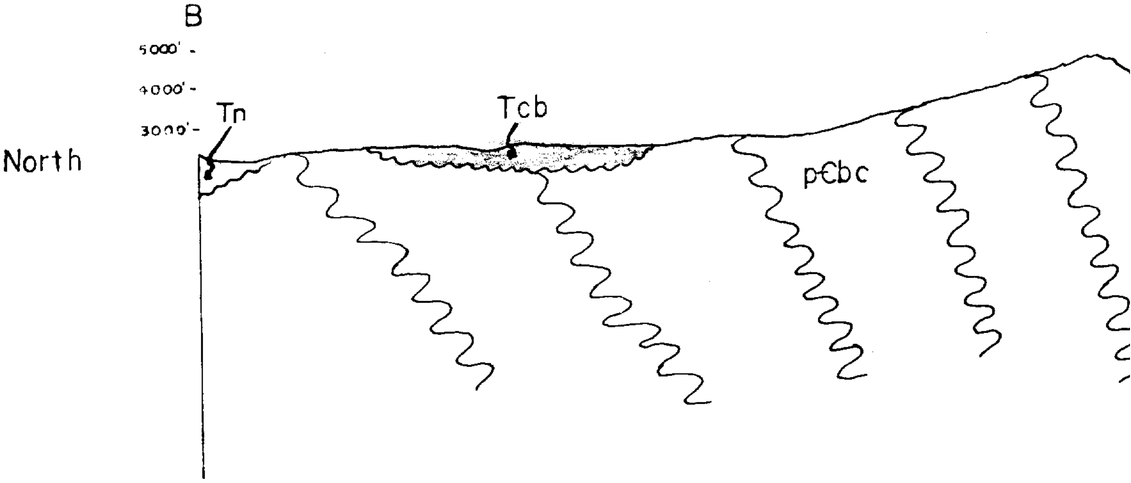
Topographic contours



74
76
67
38
40
37
56
Igloo
Mountain
4500
4000
3500

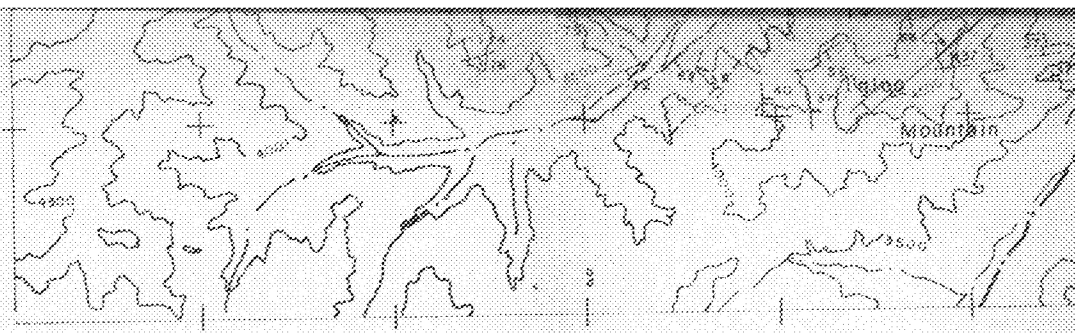


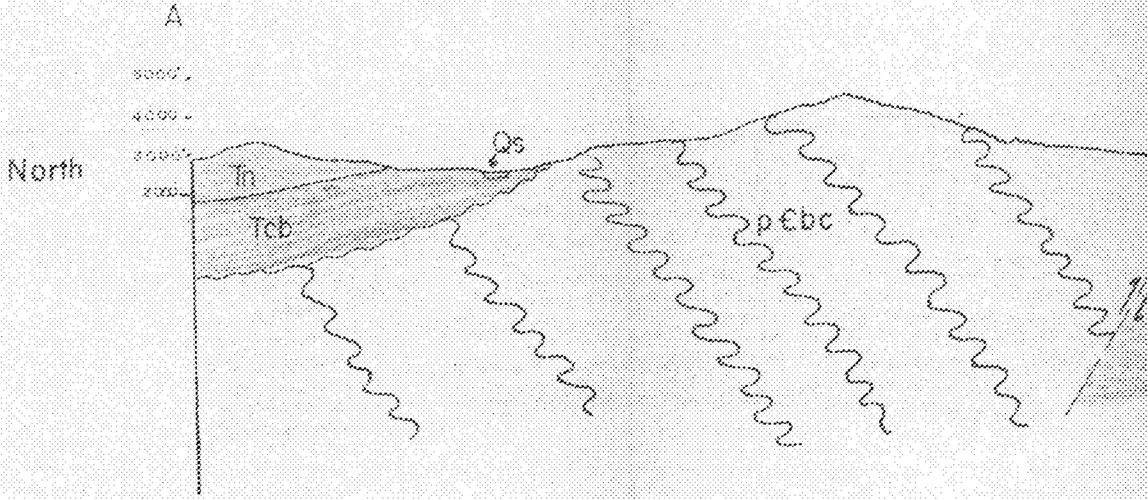
A
5000'
4000'
3000'
2000
North
Tn
Tcb
Qs
p€bc

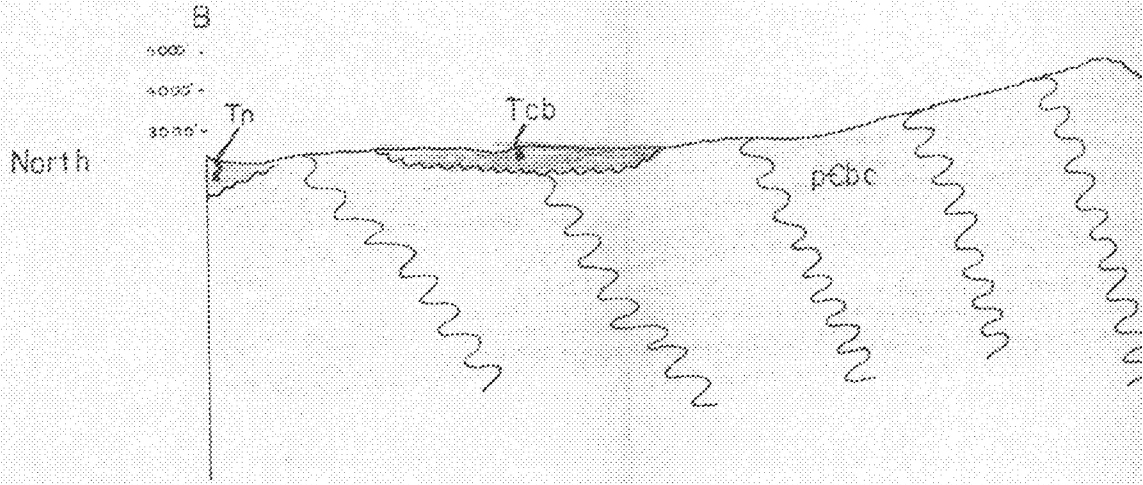


B
5000'
4000'
3000'
North
Tn
Tcb
p€bc

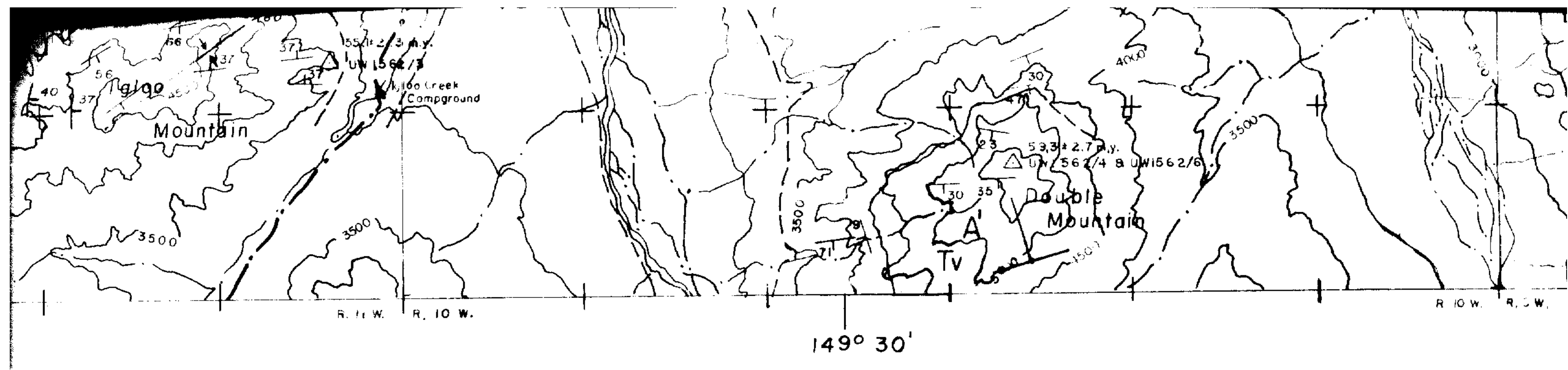
SCAL

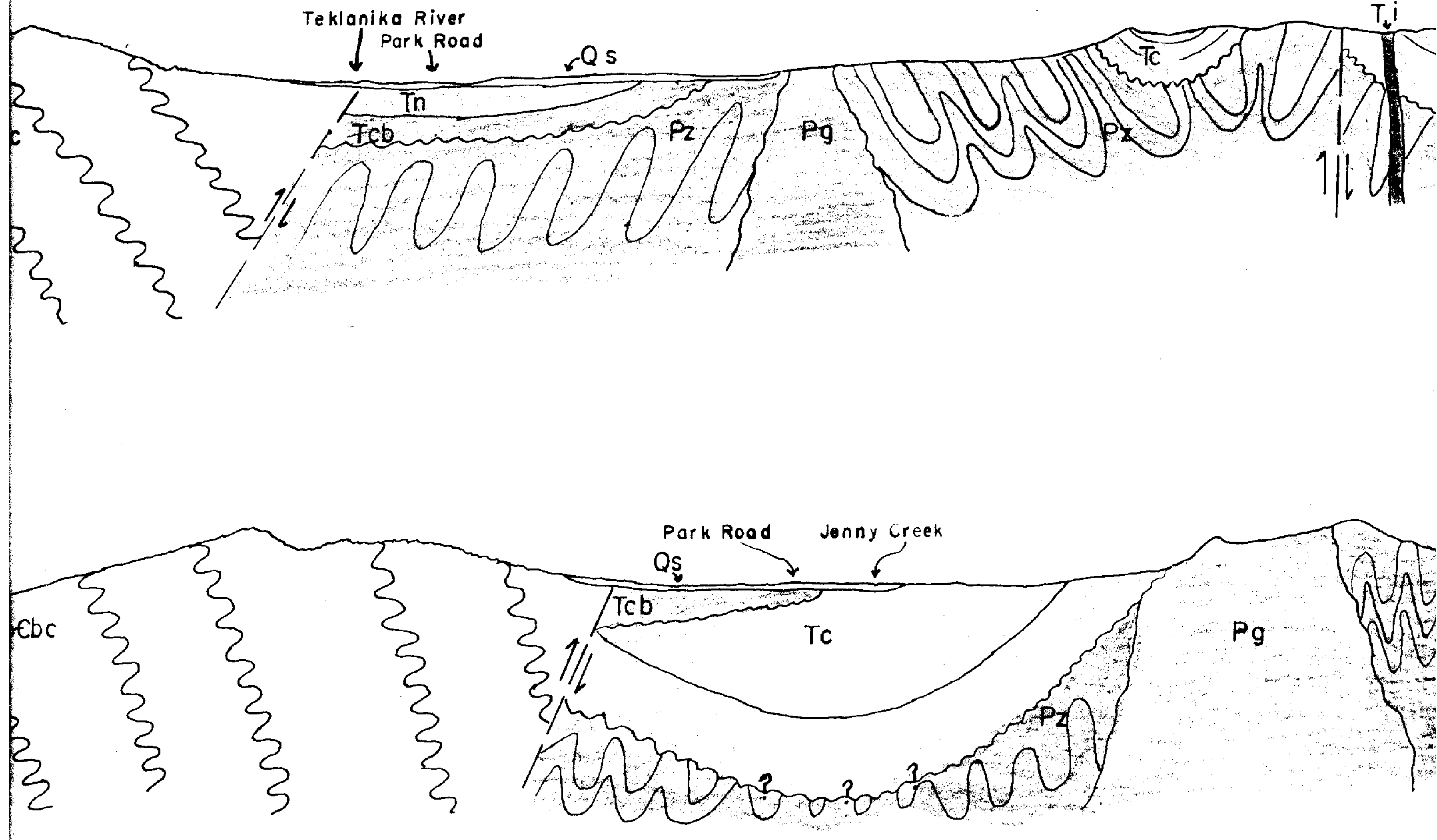

Mountain
4000
3500


A
5000'
4000'
3000'
2000'
North
Tn
Tcb
Qs
p€bc


B
5000'
4000'
3000'
North
Tn
Tcb
p€bc

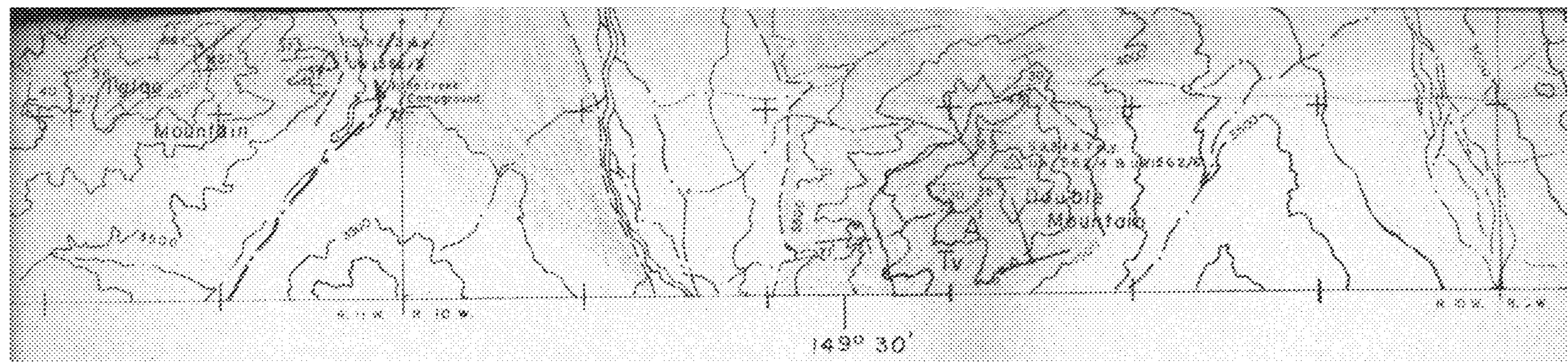
SCAL

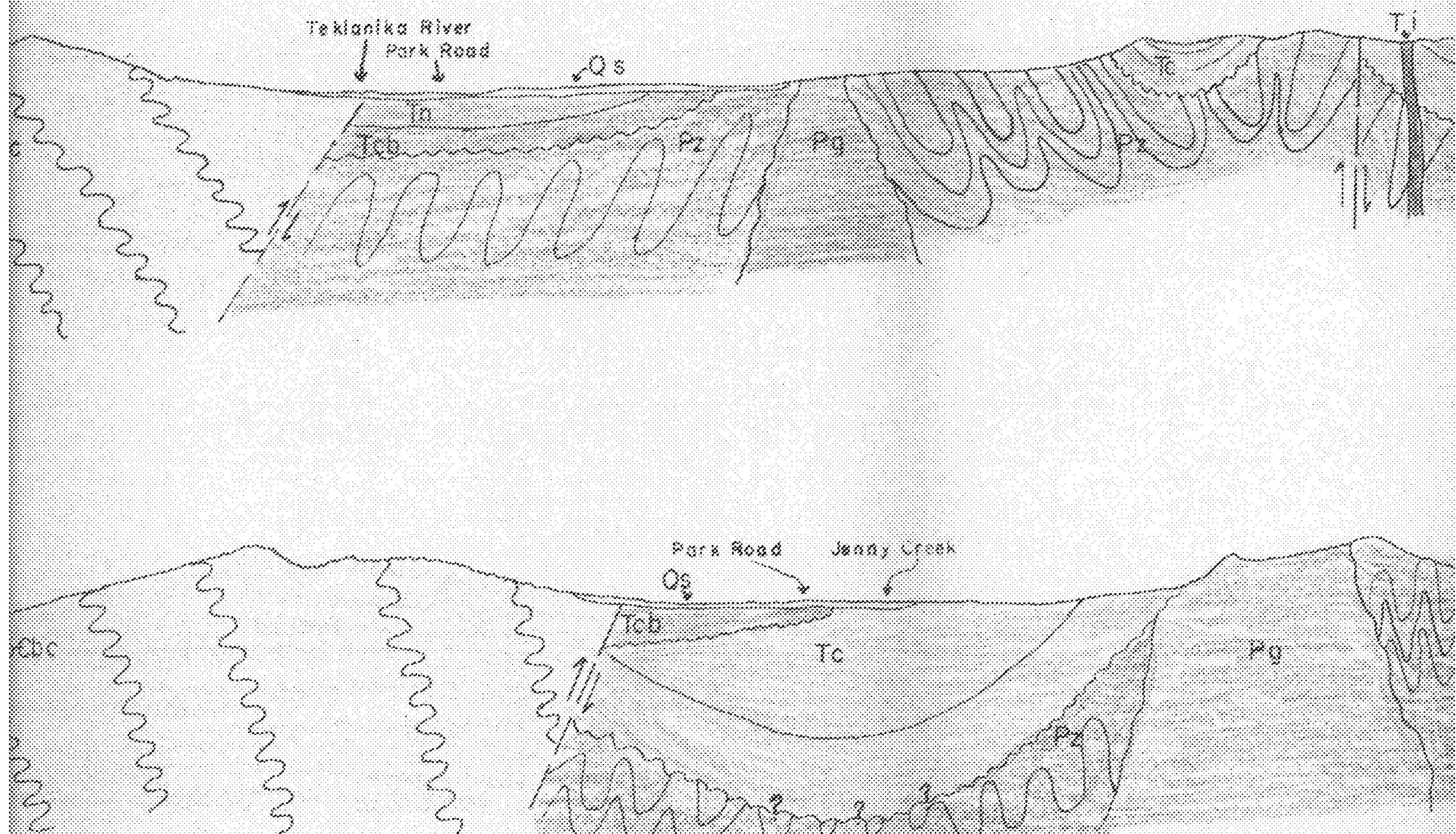




STRUCTURAL CROSS SECTIONS

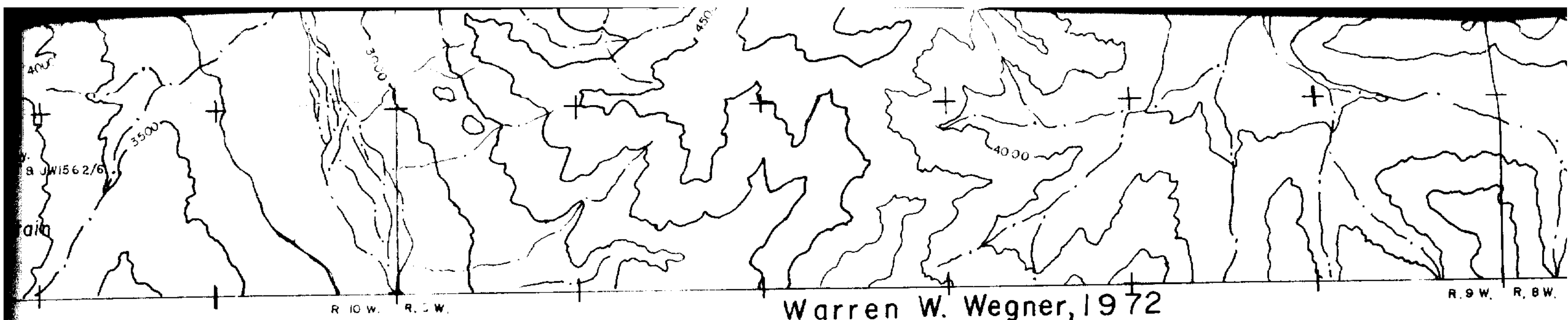
SCALE 1:63,360 NO VERTICAL EXAGGERATION



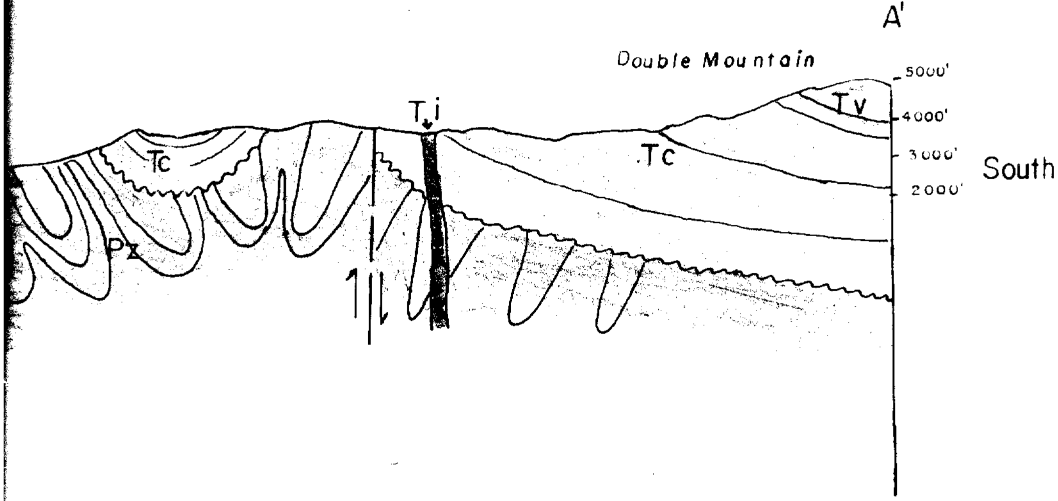


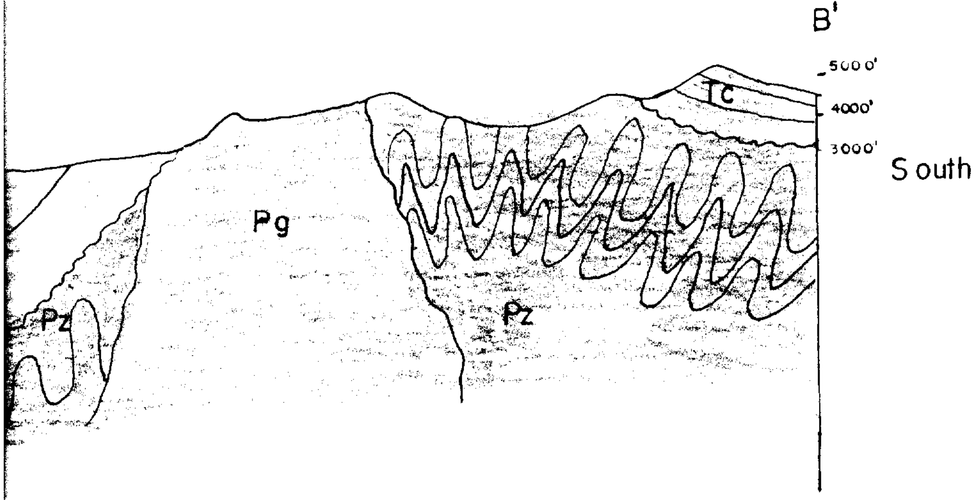
STRUCTURAL CROSS SECTIONS

SCALE 1:63,360 NO VERTICAL EXAGGERATION



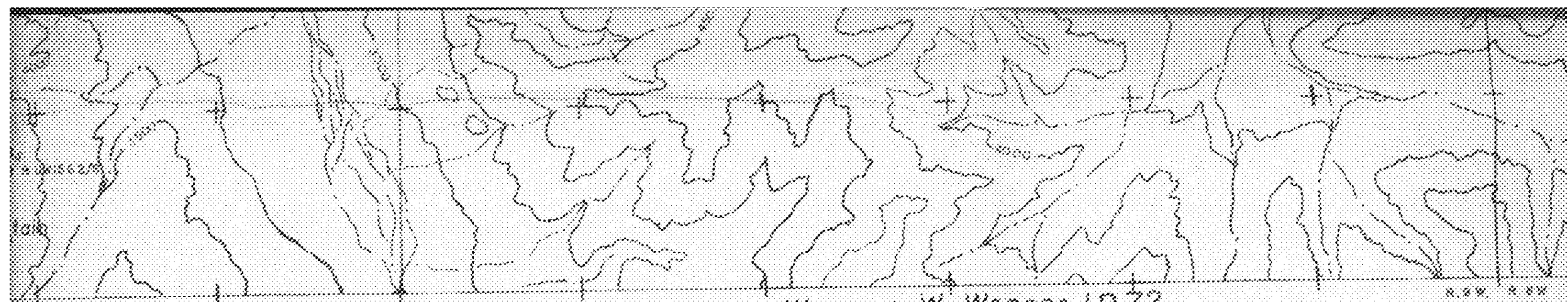
Warren W. Wegner, 1972



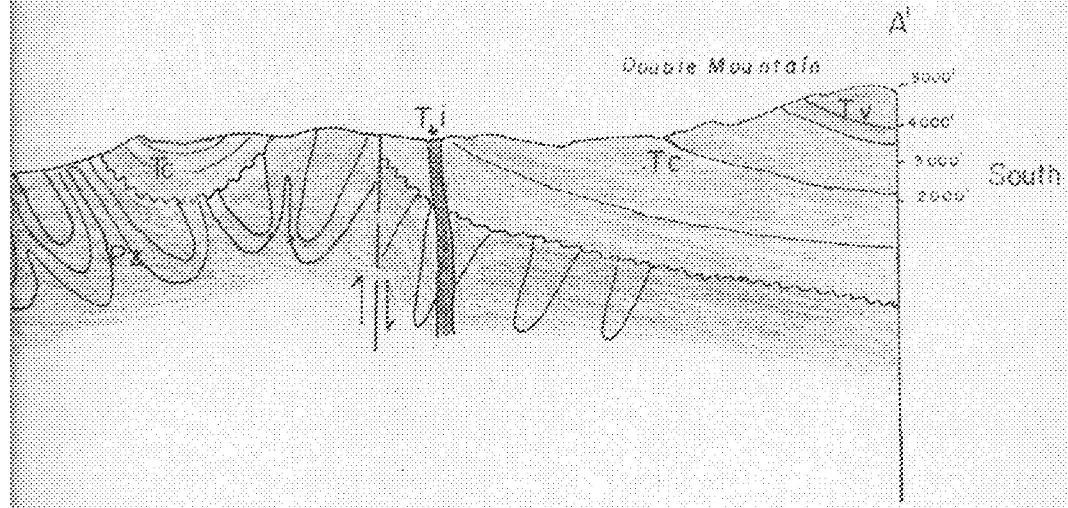


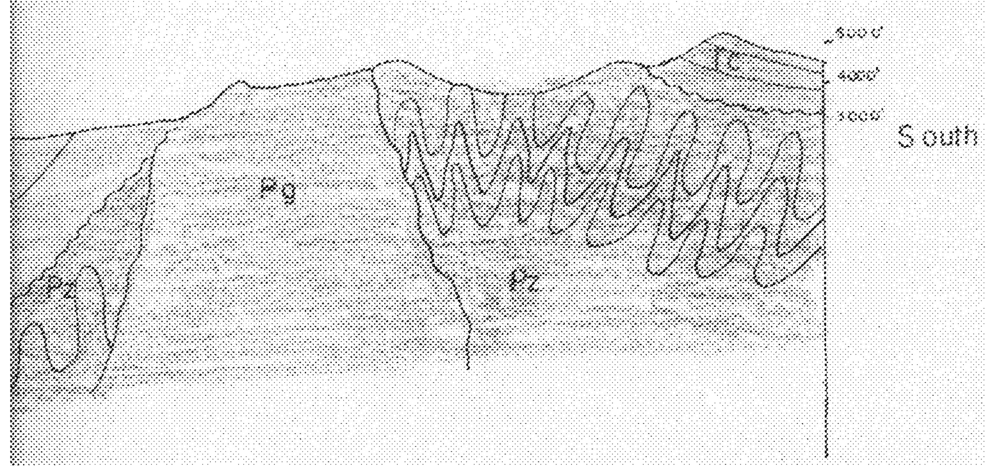
IONS

N



Warren W. Wegner, 1972





IONS

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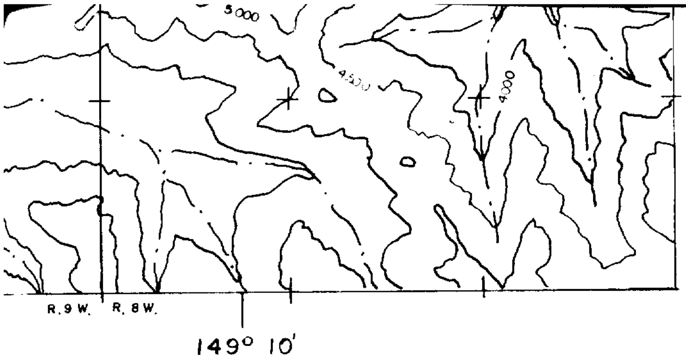


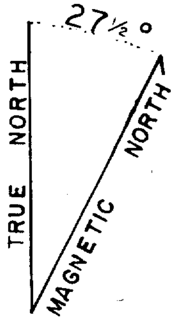
Stream

Lake

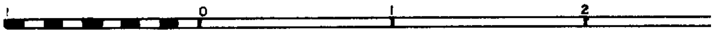
Park road

Campground x

Buildings ▪▪

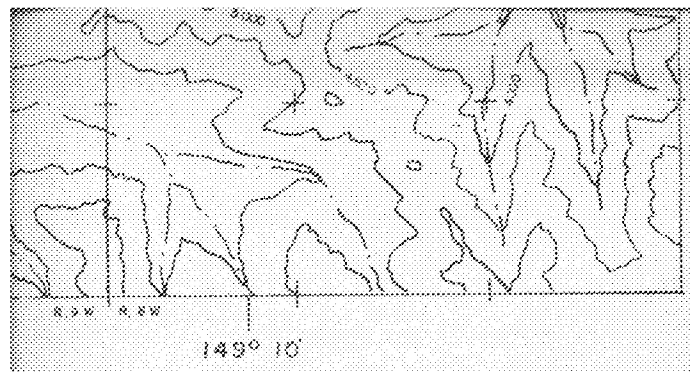


SCALE 1:63,360



CONTOUR INTERVAL 500 FE

TOPOGRAPHY FROM U.S. GE
C-5, C-6, D-5, AND D-6 QUAD



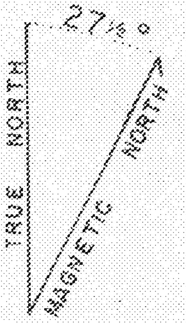
Stream 〰

Lake

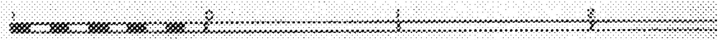
Park road - · -

Campground x

Buildings ••



SCALE 1:63,360



CONTOUR INTERVAL 500 FE

TOPOGRAPHY FROM U.S. GE
C-5, C-6, D-5, AND D-6 QUAD

Topographic contours

3000

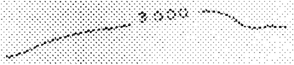
Location of cross sections

A ├──   ──┤ A'

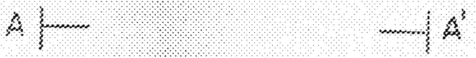
AL 500 FEET

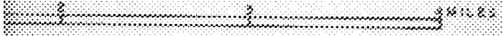
OM U.S. GEOLOGICAL SURVEY TOPOGRAPHIC MAPS OF HEALY
D-6 QUADRANGLES

Topographic contours



Location of cross sections





AL 500 FEET

OM U.S. GEOLOGICAL SURVEY TOPOGRAPHIC MAPS OF HEALY
D-6 QUADRANGLES