1981

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Recommended Citation

Johnson, Milo J., "Tectonic transport of the Newport allochthon northeastern Washington and northern Idaho" (1981). *Graduate Student Theses, Dissertations, & Professional Papers*. 7441.
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TECTONIC TRANSPORT OF THE NEWPORT ALLOCHTHON
NORTHEASTERN WASHINGTON AND NORTHERN IDAHO

By

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B.S. Wheaton College, 1978

Presented in partial fulfillment of the requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1981

Approved by:

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8/12/81
Date

ABSTRACT

Johnson, Milo J., M.S., Summer, 1981 Geology

Tectonic Transport of the Newport Allochthon, Northeastern Washington and Northern Idaho

Director: Donald W. Hyndman

The spoon-shaped Newport fault in northeastern Washington and northern Idaho separates relatively unmetamorphosed Beltian rocks from higher-grade schists and quartzites. Mineral lineations and slickensides measured near the fault suggest that transport along the low-angle Newport fault was to the northeast. Quartz fabrics of rocks adjacent to the fault zone are at least monoclinic and nearly orthorhombic with elongate maxima lying at low angles to the foliation and normal to the extension direction. Based on correlation of rocks and structures above and below the fault, it appears that the Newport allochthon originated in the Chewelah area, approximately 30 km southwest of the study area. It appears that the allochthon was transported gravitationally downslope along a zone near the top of two plutons in the area. Textures within one of these plutons suggest that it was semiconsolidated which apparently reduced the regional shear strength of the rocks. Removal of the overlying rocks evidently was accompanied by volcanism and pressure-release crystallization of the underlying magma. Rocks below the Newport fault zone are most intensely sheared in the Power Lake area because the greatest thickness of the allochthon moved across that area. Field relations suggest that transport of the Newport allochthon occurred during the Eocene.

The relationship between the Newport fault and other low-angle faults in northeastern Washington is unclear. Low-angle detachment faulting apparently occurred late in the Cretaceous as well as in the Eocene and played an important part in the tectonic development of the area. High-grade regional metamorphism culminated in the Cretaceous Period along with gravitational detachment of suprastructure from infrastructure. It is uncertain whether the Jumpoff Joe fault represents the leading edge of rocks which moved eastward off the top of the Kettle dome area during this episode of detachment. The west-dipping Newman Lake shear zone appears to flatten to the east where east-verging folds and lineations are suggestive of transport of supracrustal rocks to the east. Low-angle faults within the Purcell trench may represent the east-dipping analog to this surface along which supracrustal rocks east of the trench moved off the Kaniksu-Spokane dome.

ACKNOWLEDGEMENTS

I wish to thank the members of my committee, Dr. Don Hyndman and Dr. David Alt, for their guidance during this study and for their helpful review of several drafts of this manuscript. Dr. David Alt first introduced me to some of the problems in northeastern Washington and provided much encouragement while my field work was in progress. Dr. Don Hyndman generously took time to discuss with me many of the aspects of this study as well as offering invaluable constructive criticism in its final preparation. Dr. Don Winston and Dr. David Fountain willingly shared some of their ideas and provided fresh insight into some of the problems.

I would also like to thank my parents, Milo and Betty Johnson, for their support and encouragement throughout my graduate studies.

Mr. Milo Johnson Sr. and George and Cay Kendrick generously donated their time and effort in the final preparation of this manuscript for printing.

My good friend, Bob Pfouts, was encouraging when work was slow and was a willing companion in various forms of recreational activity which I sometimes needed badly in order to maintain my sanity.

I am especially grateful to Kathy Cheever who typed numerous early drafts of this manuscript and was a constant source of understanding, patience and companionship while completing this study.

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CHAPTER I

INTRODUCTION

Little is known about the inter-relationships of low-angle faults in northeastern Washington. Recent mapping has revealed low-angle faulting at the margin of the Kettle dome and Republic graben (Cheney, 1980; Rhodes, 1980) along with thrust faults in the Chewelah area which juxtapose originally widely separated rocks (Miller and Clark, 1975). In the study area a low-angle detachment fault, the Newport fault, separates relatively unmetamorphosed Beltian rocks from higher-grade schists and quartzites (Miller, 1974b-d). Zones of cataclasis and shearing associated with an abrupt change in metamorphic grade across these zones, south and east of the study area may represent other low-angle faults (Figure 1).

Crucial to a better understanding of the relationships between these low-angle faults includes the determination of:

1) relative age of formation of these surfaces
2) direction of tectonic transport
3) amount of tectonic transport

The purpose of this study is to examine one of these low-angle faults, the Newport fault, and try to answer the three questions posed above. This study suggests that the Newport allochthon originated in the Chewelah area and was transported along the Newport fault approximately 30 km to the northeast early in the Tertiary period. Movement probably occurred by gravity sliding initiated along a surface near the top of

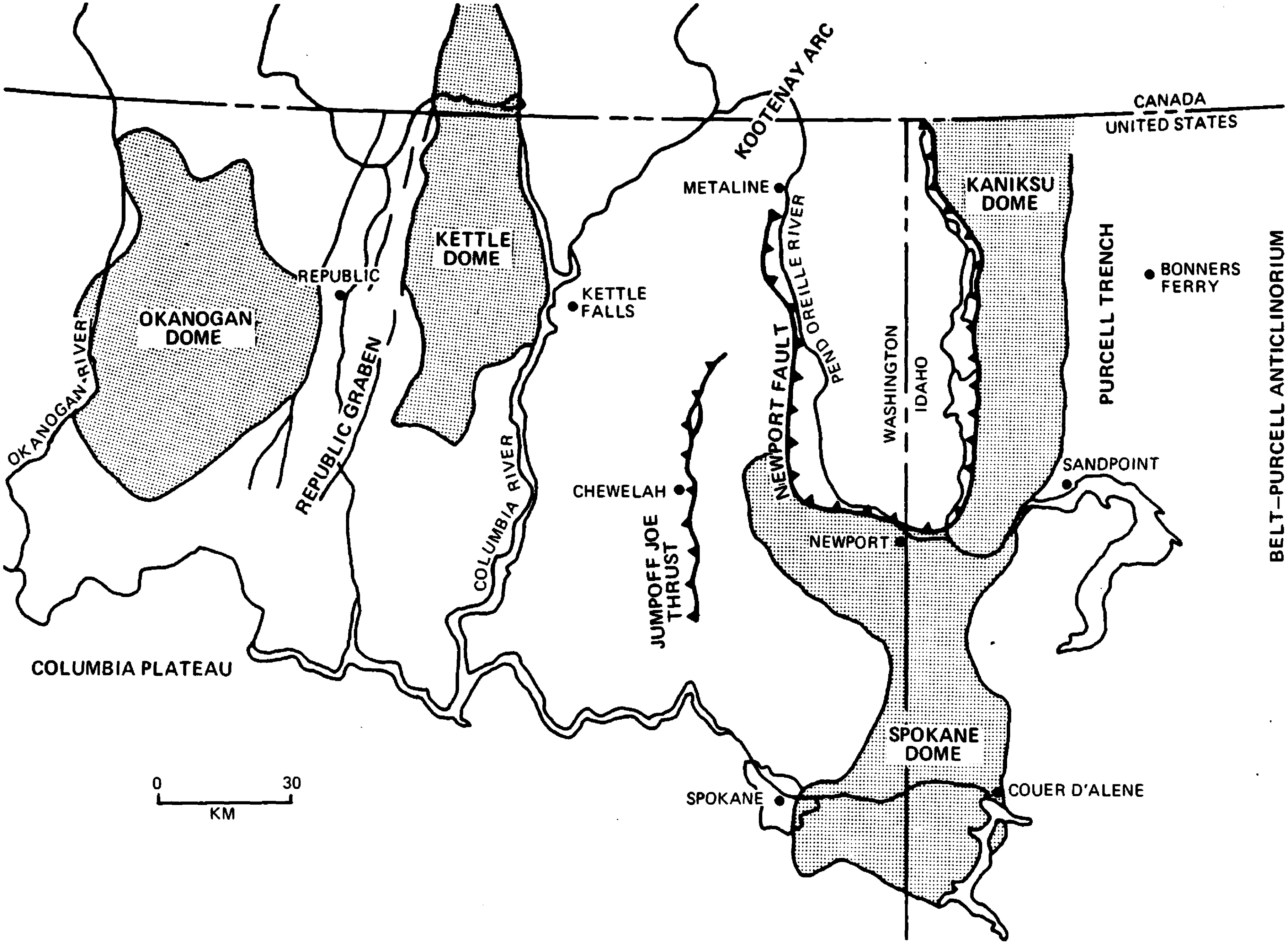


Figure 1. Generalized map of northeastern Washington and northern Idaho showing location of major structural features (modified after Cheney, 1980).

semi-consolidated plutons. These conclusions provide a basis for formulation of several models which explain the Newport fault's relationship to low-angle faults elsewhere in northeastern Washington.

Location of the Study Area

The study area lies on the western and southern margins of the Pend Oreille River valley in northeastern Washington (Figure 2). Here the Newport fault roughly parallels the course of the Pend Oreille River which changes its course from generally east-west to north-south. Outcrop is generally good just south of the east-west trace of the Newport fault near the town of Newport. Granitic rocks crop out on hills only moderately covered by low vegetation. Bedrock exposure west of the north-south trace of the fault is generally poor due to thick forest cover. Access to this area is fairly good along numerous logging roads. Fresh outcrops are generally confined to places along the roads whereas outcrops away from the roads are generally weathered and covered by lichens and moss. The Newport fault zone is well-exposed in only a few locations within the study area (Figure 9). Relief in the area ranges from 325 meters in the eastern part of the study area to about 1000 meters in the western portion.

Previous Work

Early geologic mapping in the area was concentrated largely in the Metaline area north of the study area by Park and Cannon (1943) and later followed by Dings and Whitebread (1965). Belt rocks in the report area were first mapped and described by Schroeder (1952) in the

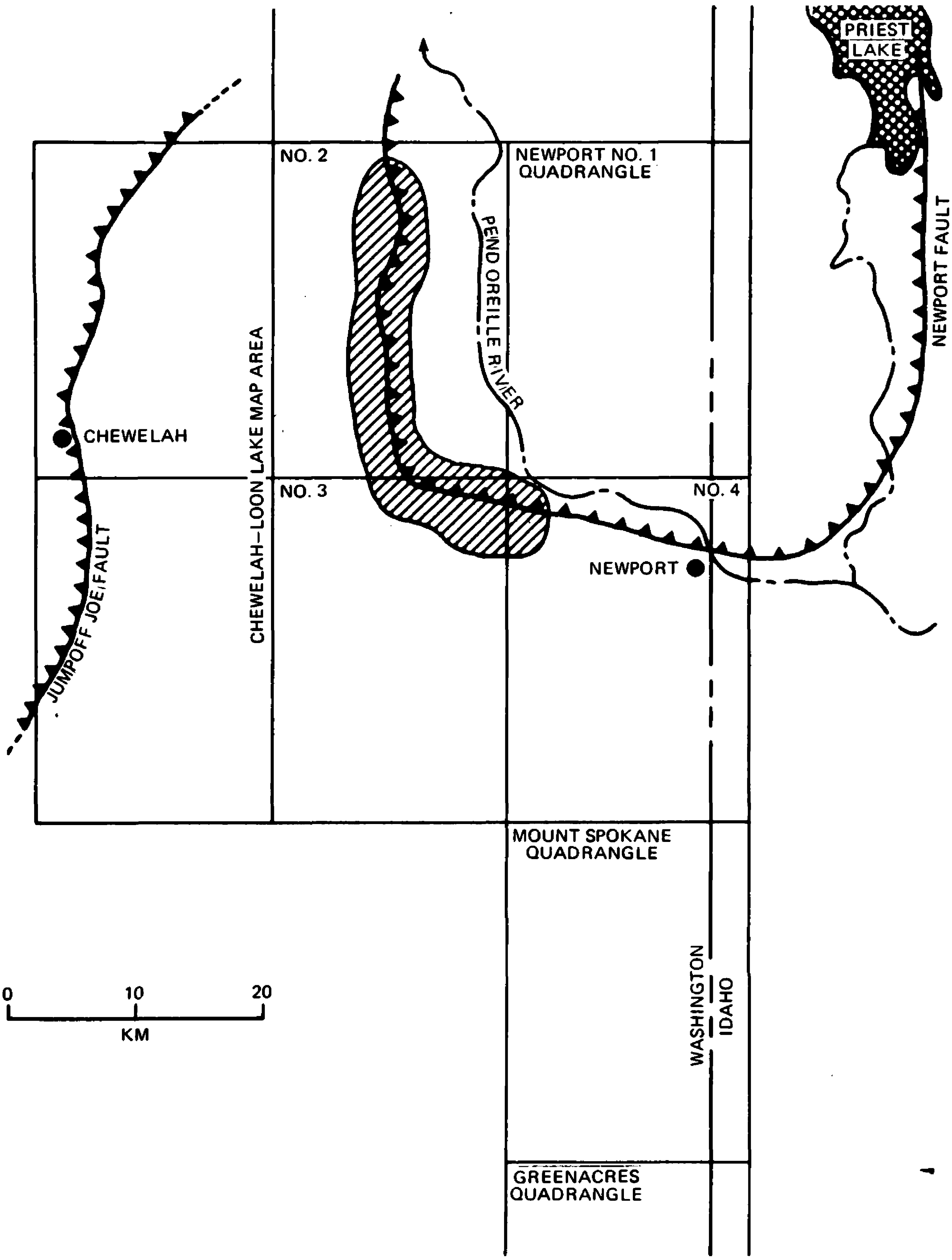


Figure 2. Map showing location of the study area (hatchured), low-angle faults, and geologic map quadrangles.

Bead Lake area, roughly equivalent to Miller's Newport no. 1 quadrangle. More recently, Weissenborn and Weis (1976) mapped the Mount Spokane quadrangle (Figure 2) south of the study area which contains high-grade rocks and intrusions of the Spokane dome (Cheney, 1980). The most recent work includes mapping of two 15-minute quadrangles in the Chewelah-Loon Lake area by Miller and Clark (1975) who first described the Jump-off Joe thrust fault. Miller (1974 a-d) mapped the Newport 30-minute quadrangle which contains the study area and a portion of the Newport fault. Potassium-argon age determinations for numerous plutons in the area are reported by Engels (1975) and Miller and Engels (1975). Barry Gager of the University of Washington is presently working on the Tiger formation within the Pend Oreille River valley.

This Study

Low-angle faulting elsewhere in northeastern Washington may be related to transport along the Newport fault. Therefore, an understanding of these faults in their regional context would aid in reconstructing the timing and movements which led to transport along the Newport fault. Therefore, this report begins with a brief review of the regional geology discussing the development of structures in northeastern Washington which lays the groundwork for inferences concerning transport along the Newport fault. A more detailed review of the regional geology is contained in the appendix to provide the reader with a greater understanding of the regional geology which led me to the conclusions contained in this report.

Results of detailed study along the Newport fault are presented in Chapter III. This is followed by conclusions concerning transport along the Newport fault and a discussion of possible relationships between low-angle faults in northeastern Washington and northern Idaho.

Rocks immediately below the sole of the Newport fault were examined for structures suggestive of transport direction along the fault. Slickensides and mineral lineations found near Power Lake were measured and recorded in the field. Hand samples were collected from near the fault for later thin-section examination. Oriented samples were also collected from several critical locations for petrofabric analysis. Orientations of quartz c-axes were then plotted on an equal-area net and contoured to facilitate petrofabric analysis and kinematic interpretation.

CHAPTER II

REGIONAL GEOLOGY

Gneiss Domes

North-central Washington is characterized by two gneiss domes separated by a structural depression, the Republic graben (Figure 1). The Kettle and Okanogan domes contain rocks and structures similar to other complexes described farther north (Reesor, 1965, 1970; Reesor and Moore, 1971; Hyndman, 1968; McMillan, 1970) and south (Hyndman, 1980; Davis and Coney, 1979). They are characterized by a high-grade infrastructure separated tectonically from a lower-grade suprastructure. This region lies at least 60 km west of the study area yet an understanding of the structural fabric of these terranes is important in order to determine the tectonic history of their formation and their possible relation to structures farther east.

The Kettle dome consists of sillimanite-grade rocks of the Tenas Mary Creek sequence (TMC) which includes metasediments, pegmatites and orthogneisses. Several workers have correlated TMC rocks with rocks of the Shuswap terrane of southern British Columbia (Parker and Calkins, 1964; Pearson, 1967; Preto, 1970; Donnelly, 1978). A wide variety of ages have been reported for rocks of the Shuswap terrane. Cheney (1980) favors a Precambrian age for the TMC rocks of the Kettle dome and suggests they may possibly be pre-Beltian. The metasedimentary rocks of the Kettle dome are intruded by numerous Mesozoic and Tertiary granitic plutons of varying compositions and textures (Cheney, 1980).

The foliation and bedding of rocks in the Kettle range define a dome > 65 km long north-south and 27 km wide with dips generally < 25° within the dome itself (Cheney, 1980). The contact between the high-grade TMC rocks of the infrastructure and the overlying low-grade suprastructural rocks east of the dome is a zone of intense shearing and cataclasis which appears to extend all along the domes's eastern margin and dies out as it wraps around its southern end. Cataclasis appears most intense at the eastern edge of the dome as does development of a penetrative mineral lineation and streaking lying within the cataclastic foliation. Slickensides lying on shear surfaces parallel to the foliation maintain a consistent orientation parallel to the trend of the mineral lineations yet both gradually die out westward across the dome.

Folds are developed at all scales within the dome although the smaller type predominates. Rhodes (1980) shows that the earliest isoclinal folds trend east-west and are cut by the cataclastic foliation. Donnelly (1978) has identified four phases of folding and has shown their similarity to phases identified in domes farther north. Large steep faults that cut rocks of the dome are probably pre-Tertiary (Cheney, 1980).

The Okanogan gneiss dome (Fox and Rinehart, 1971; Fox and others, 1976) lies west of the Kettle dome between the Republic graben and the Okanogan River. The plutonic and high-grade rocks of the infrastructure were originally assigned to the Colville batholith (Pardee, 1918) by several workers (Waters and Krauskopf, 1941; Yates and others, 1966). Waters and Krauskopf concluded that the high-grade cataclastic gneisses were the protoclastic border zone of a large batholith. These highly crushed and sheared rocks at the western margin of the dome gradually disappear eastward as they wrap around the northern and southern reaches of the dome. Snook (1965) later renamed these rocks the Tonasket Gneiss. Rocks included in the Tonasket Gneiss are of metasedimentary and metavolcanic parentage (Snook, 1965; Waters and Krauskopf, 1941; Fox and others, 1976). A discontinuous envelope of granitoid gneiss, probably of igneous parentage, surrounds the Tonasket Gneiss.

Penetrative mineral streaks and lineations lie within the cataclastic foliation describing the dome and maintain consistent orientation west-northwest. Fold axes in the gneisses are parallel to the trend and plunge of the lineation and both are roughly contemporaneous with crystallization (Snook, 1965). The zone of shearing at the western margin of the dome consists of thinly layered mylonite to very fine-grained cataclastic gneiss. Cataclasis, foliation and lineation become poorly developed eastward over the dome. Fractures trending north to northeast are commonly filled with epidote and obliquely truncate the mylonitic foliation. This fracture pattern is most intense in the western part of the dome and dies out completely on the eastern flank (Snook, 1965).

Republic Graben

The Republic graben is a structural depression lying between the Kettle and Okanogan domes. Rocks within the graben range in age from late Paleozoic to Recent although Eocene sedimentary and volcanic rocks generally dominate the rock types. The nature of this structure is in debate as it appears that the graben is bounded on the west side by east-dipping low-angle faults (Cheney, 1980). Cheney suggests that the Eocene rocks within the graben may comprise a synclinal allochthon and represent a regional volcanic and tectonic event not confined to the graben. High-angle faults bound the graben on the east while those within the graben generally parallel its trend.

Kootenay Arc

The crescent-shaped Kootenay arc lies immediately to the east of the Kettle dome (Figure 1) and the Shuswap metamorphic complex farther north in British Columbia. It consists of folded and faulted rocks ranging in age from Proterozoic to middle Jurassic. In British Columbia, Ross (1970) postulates that eastward-verging allochthonous rocks of the western Kootenay arc are separated by a major sole thrust from westward-verging parautochthonous rocks in the eastern Kootenay arc. In northeastern Washington the west-dipping Jumpoff Joe thrust separates eastward-verging structures on the west from westward-verging folds structurally below (i.e. east of) the fault. Ross concludes that the earliest structures of the Kootenay arc formed by easterly movement of nappes with the latest deformation resulting in the backfolding of these nappes (westward verging folds) off the rising Purcell basement. An east-west-trending thrust belt trends obliquely across the trend of the earlier formed folds of the Kootenay arc (see Figure 3) (Yates, 1964, 1971). In any case, dominant movement apparently was from west to east. The zone of cataclasis and shearing located at the eastern edge of the Shuswap metamorphic complex may represent a gently-dipping

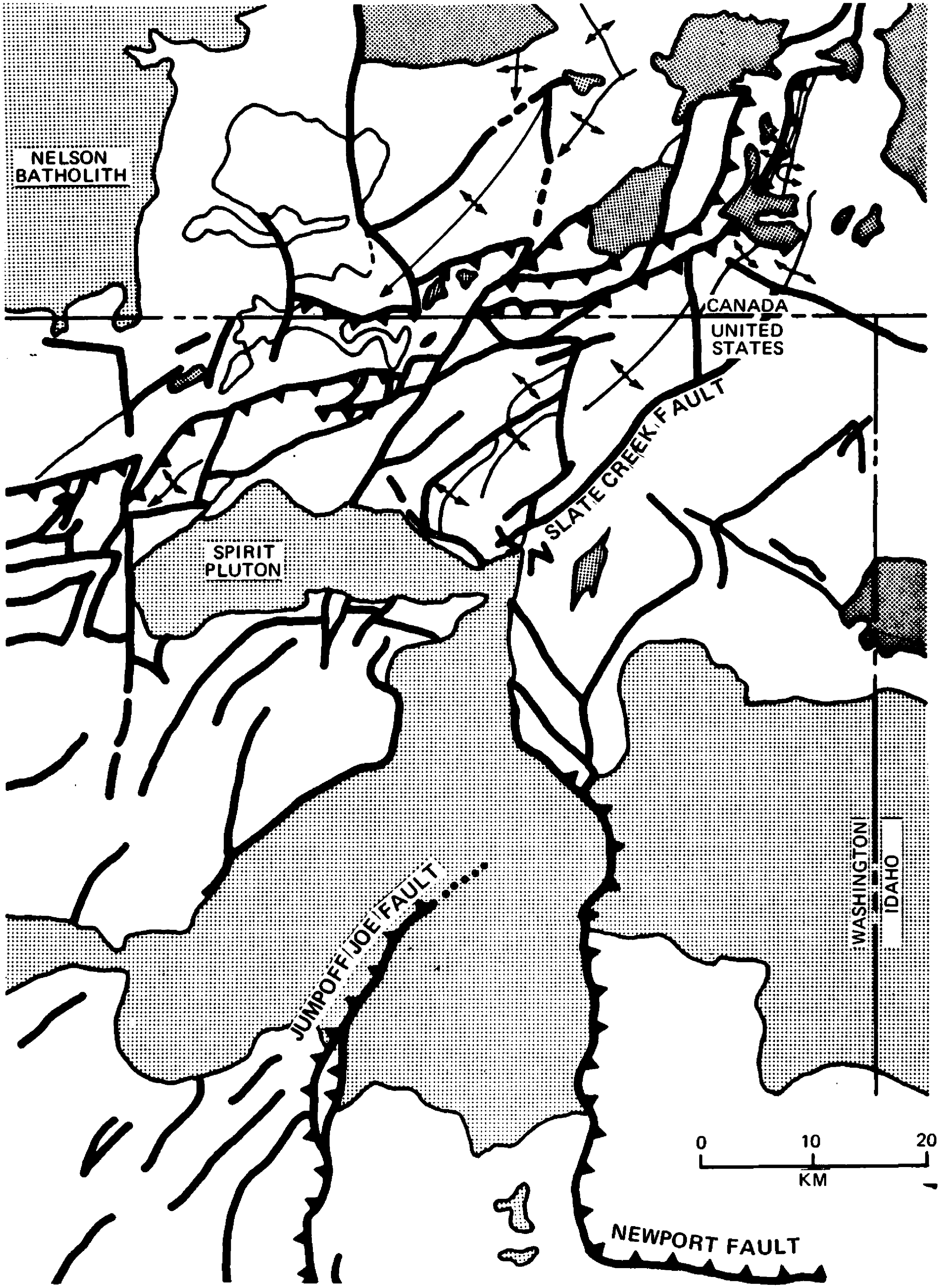


Figure 3. Map showing northeast-trending structures of the Kootenay arc (modified after Yates, 1971).

detachment surface along which rocks of the Kootenay arc moved off the eastern part of complex during dome formation (Read, 1977). This movement probably occurred late in the development of the Kootenay arc.

Discussion

It is critical to determine the relative ages of the detachment surface and rise of the gneiss dome in order to more fully understand the movements that produced the structures within and around the dome. Identification of the nature and extent of the unloaded supracrustal rocks would certainly aid in reconstructing those events which precede and coincide with formation of the dome but often these rocks have been severely deformed thus obscurring their relationship with rocks of the infrastructure.

Mineral lineations and slickensides maintain consistent east-west trend regardless of the trend of the foliation which suggests they formed prior to deformation of the foliation. Therefore, it appears that the detachment surfaces in both the Kettle and Okanogan domes formed before rise of the dome.

The consistent trend of mineral lineations and slickensides within each dome also suggests a unidirectional removal of supracrustal rocks off the domes. This probably occurred along a flat detachment surface rather than gravitational sliding off the present dome. If the dome predated the detachment surface, then the dome should exhibit a radial movement of the rocks off the dome.

Snook (1965) attributed the mylonites in the Okanogan dome to a distributed flat thrust which was later folded. Cheney (1980) believes that upper TMC rocks of the Kettle dome were subjected to shearing along a decollement surface and later deformed during a period of large-scale Tertiary folding. Snook (1965) considers small-scale folds within the Okanogan dome as products of an earlier period of deformation directed at 90° to those forces which produced the lineation within the mylonites. The foliation outlining these folds precedes development of cataclasis in the Tonasket Gneiss. The orientation of these fold axes, however, may have been produced through the same movements which produced the cataclasis and mylonites. Fold axes oriented at high angles to planes of shear may be rotated into the plane of shearing aligned in the transport direction (Hobbs and others, 1976, p. 286-287; Hyndman and others, 1975). Both the lineation and alignment of the fold axes within both domes may have originated by shearing along a flat zone parallel to the foliation.

Lateral asymmetry of cataclasis and lineation in both domes indicates differential shearing intensities along the detachment surface. If the variation in intensity were a result of erosion after folding of the surface then a concentric pattern of intensities should be preserved with the greatest intensities located at the margins of the dome. In both the Kettle and Okanogan domes the cataclasis and mylonitization are best developed along only half of the circumference of the dome. A similar pattern found in the Bitterroot dome in western Montana is explained by the passage of a thicker portion of supracrustal rocks across one flank of the dome (Hyndman, 1980). This evaluation for the Kettle dome may be somewhat tenuous because the western portion of the dome is truncated by the Sherman Creek fault.

Based on these relations, I favor a movement scenario in which supracrustal rocks moved off the Okanogan dome area along a gravitationally controlled flat detachment zone to the west-northwest whereas lineations within the Kettle dome suggest that those rocks moved eastward off the area of the dome before final rise of the dome (see Figure 4).

There is evidence in both domes for late stage, brittle-style deformation within the cataclastic rocks again most intensely developed within the mylonite zones of each dome. In the Okanogan dome directionless microbrecciation associated with low-temperature secondary minerals in the mylonites suggest that deformation took place at shallower depths than the movements that formed the folding and earlier lineations (Snook, 1965). In the Kettle dome, penetrative development of slickensides at outcrop scale which parallel the trend of mineral streaking and lineation suggest they formed under more brittle conditions than those that typify the earlier lineations. Some late-stage movement may have been post-Eocene as the Kettle River fault cuts synclinal Eocene-age rocks (Rhodes, 1980). In the Bitterroot dome, Hyndman considers progressive unloading of the supracrustal Sapphire tectonic block responsible for a change in deformational style, from deep-seated plastic flow to shallow, brittle shearing.

The Swimptkin Creek pluton of granitic composition cuts the Okanogan dome and yields concordant biotite and hornblende K-Ar dates of 48.0 and 48.2 m.y. (Eocene) respectively. The Okanogan dome cuts rocks which include the Anarchist Group and the Kobau Formation of Permian and Triassic age (Rinehart and Fox, 1972; Waters and Krauskopf,

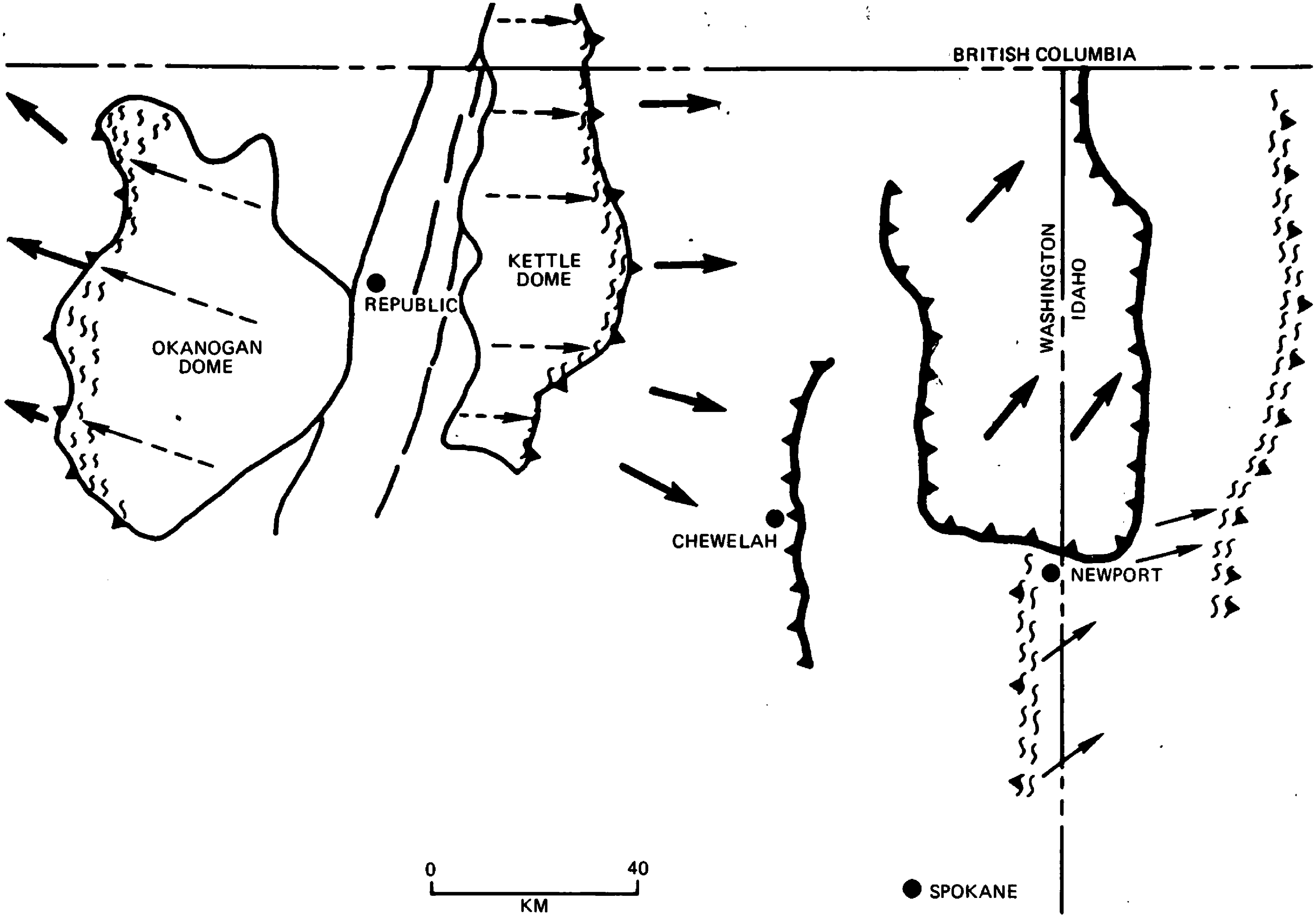


Figure 4. Interpretive sketch of major structural features of northeastern Washington and northern Idaho showing proposed transport directions of supracrustal rocks (large arrows). Small arrows show transport direction of overlying rocks suggested by autochthonous rocks in infrastructure.

1941). Therefore, metamorphism in the dome took place between late Triassic and Eocene time. Based on radiometric age dating of rocks in the dome, Fox and others (1976) suggest that high-grade metamorphism culminated in the Cretaceous and rocks of the dome cooled slowly through successive temperature thresholds of various minerals yielding discordant ages on a number of samples.

Based on correlations with rocks of the Okanogan and Shuswap domes, Rhodes (1980) assigns a Cretaceous age to the high-grade metamorphism in the Kettle dome. Since the shearing deformation which produced the lineation and mylonitization occurred partly coeval with the high-grade metamorphism (Snook, 1965; Fox and others, 1976; Rhodes, 1980), tectonic unroofing of both the Kettle and Okanogan domes probably took place late in the Cretaceous.

Development of the gneiss-dome terrane in north-central Washington most likely began with igneous activity in the form of rising magmas resulting from the development of a Benioff zone to the west (Price, 1980). This thermal activity was accompanied by regional metamorphism and partial melting of crustal rocks. Thermal expansion led to regional uplift of the rocks producing a regional slope with sufficient gravitational potential to initiate movement of supracrustal rocks downslope. Gravitational gliding was probably facilitated by plastic flowage in the rocks at considerable depth. Structures found within the two domes suggest that supracrustal rocks moved westward off the Okanogan dome and eastward off the Kettle dome. As a consequence, I infer that the topographic high at the time of detachment lay somewhere between the two domes approximately in the present-day location of the

Republic graben (assuming that the domes themselves have not been thrusted). This region upslope from the detaching rocks presumably became extended in a fashion similar to rocks located at the head of a large landslide. It is conceivable that such a zone of extension played an important role in the development of a "structurally weak zone and area of subsequent rifting" (Staatz, 1964, p. F58) which ultimately resulted in development of the Republic graben.

As supracrustal rocks moved off the domes along a plastic-like zone of shearing, rocks of the infrastructure became lineated and developed a cataclastic foliation. Pre-existing folds were rotated into the plane of shear and trend parallel to that of the mineral lineations and slickensides. Effects of shearing and cataclasis became most pronounced on the flank in the direction of tectonic transport where the thickest portion of overlying rocks would have passed. Late-stage brittle-style deformation structures, such as microbrecciation and slickensides formed within the detachment zone as those rocks became shallow with removal of the overlying cover rocks. Low-angle faults at the eastern margin of the Kettle dome (Kettle River fault) and on the west side of the Republic graben may denote an Eocene or later period of gravitational movement off the domes. The general aspects of this model are the same as those proposed for formation of the Bitterroot dome (Hyndman and others, 1975; Hyndman, 1980).

As demonstrated above, cataclasis and shearing preceded rise of the dome. Four large-scale open folds parallel to smaller and earlier folds and lineations within the Okanogan dome mapped by Snook (1965), are outlined by the cataclastic foliation and, therefore, probably formed along with rise of the dome. Several east-west-trending, large-scale open folds have been mapped in the Grand Forks area by Preto. Such folds are characteristic of gneiss domes in the Shuswap and since they postdate the cataclastic foliation, they may be related to rise of the dome.

In the Bitterroot dome, Hyndman directly addresses the problem of the origin of those forces which ultimately folded the gneisses into their present domal shape. He proposes a model of isostatic rise of the infrastructure in response to tectonic denudation of the dome. Implicit in this model is isostatic compensation within a relatively hot, mobile crust or upper mantle (Hyndman, oral communication, 1980).

Structures found in rocks of the Kootenay arc may represent deformation arising from their tectonic accretion onto the continental margin (Price, 1980) and subsequent tectonic unroofing of the metamorphic-core complexes. Latest deformation reflecting denudation of the domes would have occurred shortly after metamorphism and rise of those terranes in Cretaceous time. Identification of the nature and extent of the cover rocks is speculative but it is interesting to note that the width of the Kettle dome west of Kettle Falls roughly coincides with the distance from the shear zone near the Columbia River eastward to the Jumpoff Joe thrust (see Figure 1). It is uncertain whether the Jumpoff Joe thrust represents the leading edge of the detached cover rocks. Thrust faults in the Northport and Deep Creek areas formed late in the development of the Kootenay arc and may be related to unroofing of the domes.

In this model, as the suprastructure moved to the east, folds in the Chewelah area were tightened, raised and flopped back westward on themselves. I attribute this apparent reversal of transport direction to a buttress effect from the east. Geophysical evidence from farther north may suggest that the approximate location of the continental margin lies underneath the Kootenay arc (Price, 1980). An abrupt increase in thickness of the continental craton forming a step in this area could account for this buttress. Alternatively, the buttress effect may be due to eastward crowding of these rocks against the rising or existing Kaniksu dome.

Study Area

Schroeder (1952) originally named rocks of the Newport allochthon as the Newport Group but Miller (1974a) later correlated these units with those of the Belt Supergroup in the Coeur D'Alene district and around Pend Oreille Lake. The allochthon contains a complete section of Belt rocks from the Prichard Formation up through the Striped Peak Formation. It forms a steeply west-dipping homoclinal section striking north-south (Figure 5). Barnes (cited in Miller and Clark, 1975) mapped east-dipping beds in the Idaho portion of the allochthon and named this fold the Snow Valley anticline. Dips generally range from 50 to 75 degrees with some beds locally overturned. The Addy Quartzite unconformably overlies the Striped Peak Formation and in turn is overlain by rocks of Paleozoic age. This sequence is cut on the west and east by the synformal Newport fault (see Figure 5). Numerous normal-slip faults, generally trending northerly, cut these rocks and apparently

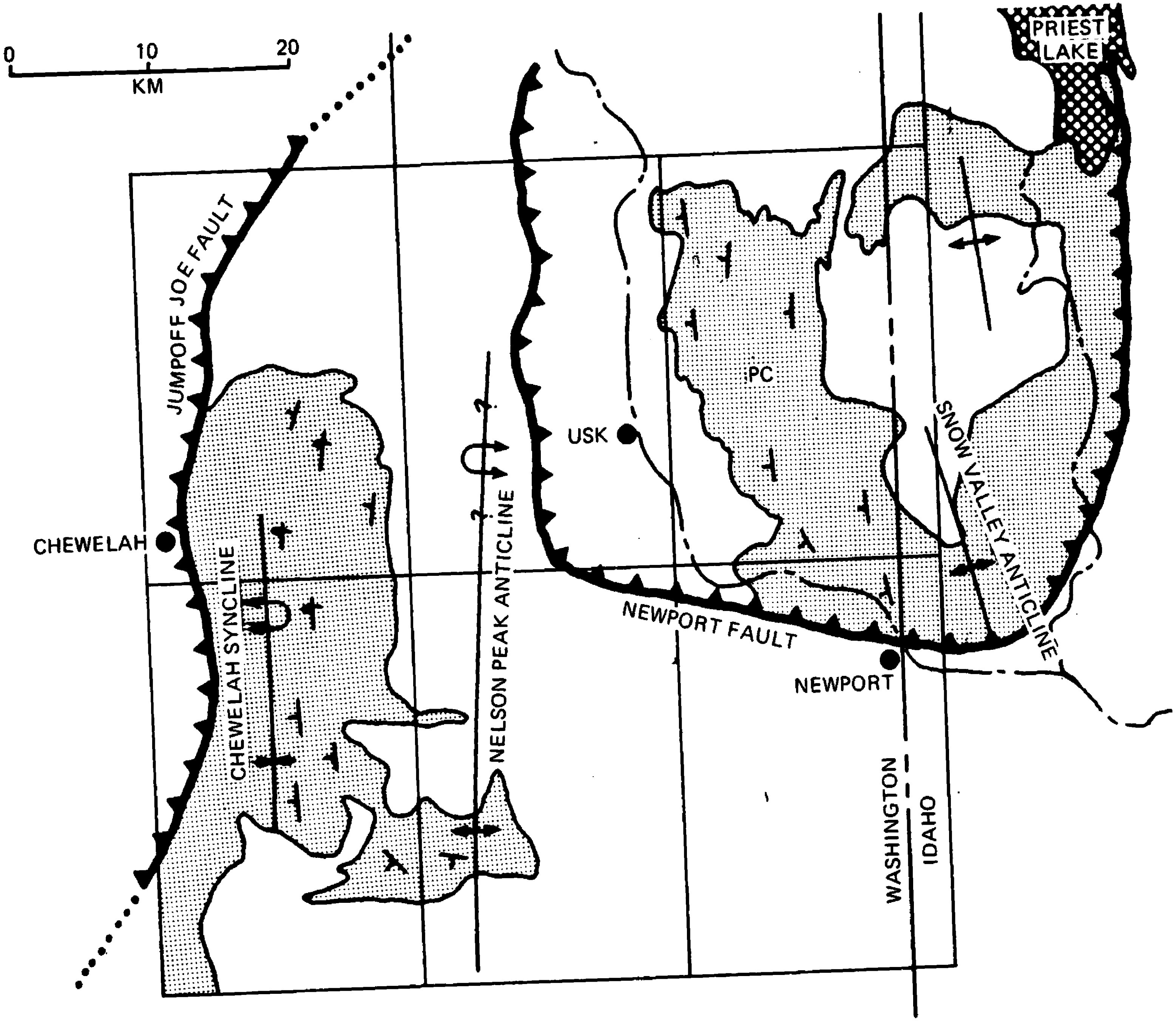
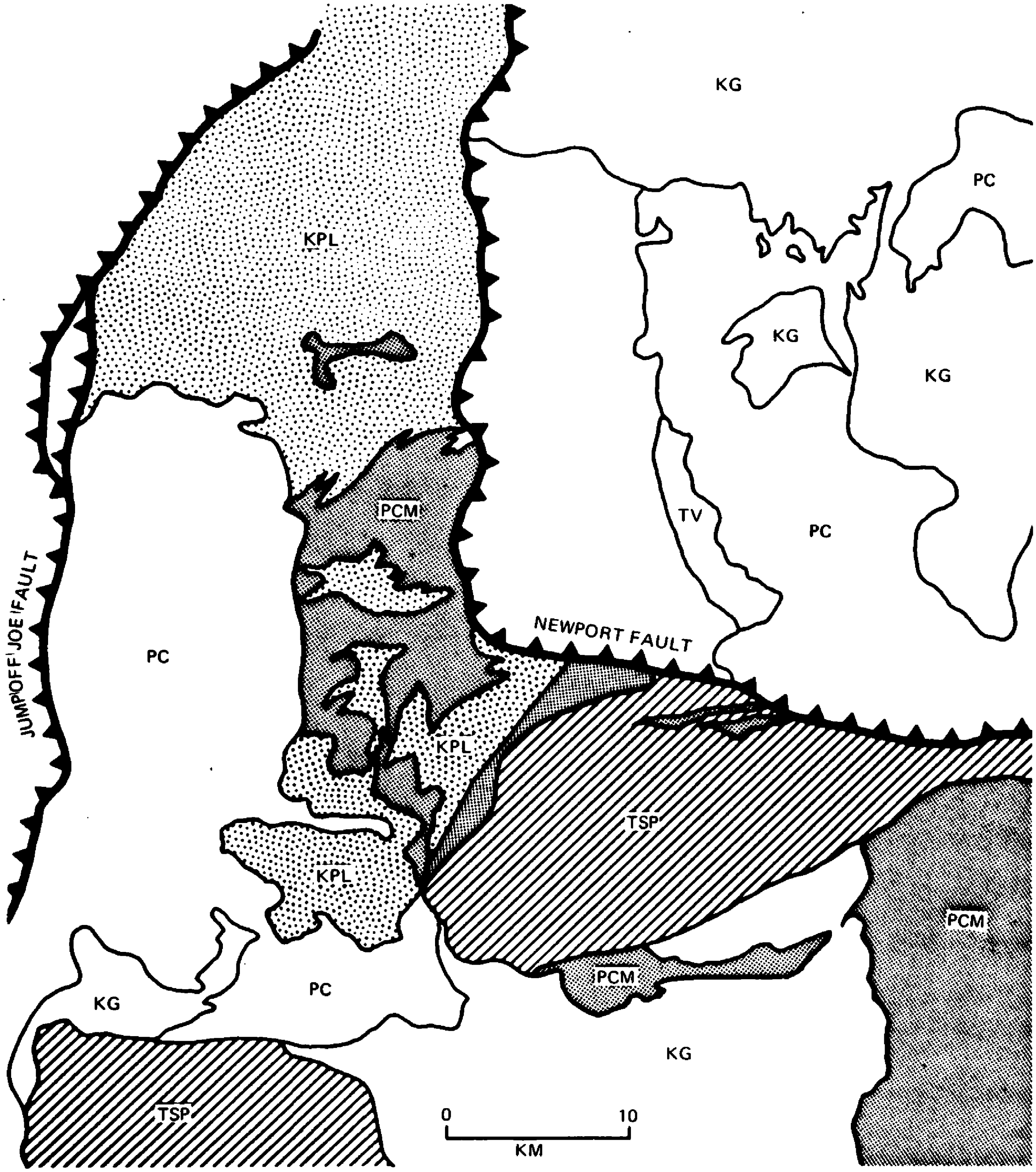


Figure 5. Structural setting of the study area (modified after Miller and Clark, 1975).

all formed during the same period of faulting (Miller, 1974a). Faulting in the area pre-dated extrusion of the Eocene Pend Oreille Andesite.

Tuff and tuffaceous shale beds of the O'Brien Creek Formation dip gently west in the vicinity of Skookum Creek and are overlain by flows of the Eocene Sanpoil Volcanics or alternatively by Eocene conglomerates of the Tiger Formation (Pearson and Obradovich, 1977). Light and dark-gray porphyritic lava flows lie along the east side of the Pend Oreille River valley (Figure 6) in the vicinity of Skookum Peak. Originally named the Pend Oreille Andesite by Schroeder (1952), these rhyodacite flows were later correlated with the Sanpoil Volcanics by Pearson and Obradovich (1977) who obtained K-Ar dates of 51.0 m.y. on hornblende and 50.4 m.y. on biotite.

Poorly sorted and poorly bedded conglomeratic beds in the Pend Oreille River valley within the Metaline quadrangle were named the Tiger Formation by Park and Cannon (1943). They infer (p. 23) that clastics of the formation were primarily locally derived and probably deposited in streams and lakes occupying a "valley similar to that existing today." Schroeder and Miller assigned conglomeratic beds within the Newport map area to the Tiger Formation. Beds of the Tiger Formation overlie the O'Brien Creek Formation, Sanpoil Volcanics and several Precambrian and Cambrian formations. The Tiger generally lies to the east of the Newport fault below the 1100-meter elevation although Miller (1974b) indicates that it may partially overlap the trace of the fault. Park and Cannon considered the Tiger to be Tertiary which was later refined to Eocene by Pearson and Obradovich (1977) based on the



LEGEND
TSP – SILVER POINT QUARTZ MONZONITE
TV – PEND OREILLE ANDESITE
KPL – PHILLIPS LAKE GRANODIORITE
KG – UNDIVIDED CRETACEOUS GRANITIC ROCKS
PC – PRECAMBRIAN BELT ROCKS
PCM – PRECAMBRIAN METAMORPHIC ROCKS

Figure 6. Map showing general geology around the study area.

formation's conformable relationship to the underlying Sanpoil Volcanics.

Rocks beneath the sole of the Newport fault and bounded on the west by the eastward-verging Jumpoff Joe thrust consist of a complete section of Belt rocks, Paleozoics and numerous intrusions ranging in age from Jurassic to Tertiary (Miller, 1974b-c; Miller and Clark, 1975). The sedimentary rocks generally trend northerly and either dip steeply to the west or are overturned to the east. Miller and Clark report two large-scale folds within this area which they name the Chewelah syncline and the Nelson Peak anticline. These two folds and their location relative to folds farther east are shown in Figure 5. Near the southern border of the area, the beds strike northwest and farther north swing around to the northeast where the folds become progressively more overturned to the west.

Lowermost Belt rocks belonging to the Prichard Formation crop out in the eastern portion of the Chewelah-Loon Lake map area and appear to grade eastward into higher-grade metamorphic rocks in the Newport quadrangle. These metamorphic rocks consist of muscovite-biotite schist and micaceous quartzite and presumably represent high-grade rocks derived from the Prichard based on structural continuity, similar lithology, rusty weathering and mafic rock layers which may represent metamorphosed diorite sills of the Prichard (Miller, 1974b-c).

The Phillips Lake Granodiorite underlies much of the area just to the west and northwest of the Newport fault in the study area (Figure 6). Miller and Clark (1975) first mapped and described this unit while mapping in the Chewelah-Loon Lake area. It consists primarily of biotite-muscovite granodiorite of varying compositions. Numerous dikes cut the granodiorite and consist largely of medium to fine-grained granite with subordinate amounts of aplite and pegmatite (I.U.G.S classification used in this report, Streckeisen, 1976). The dikes become progressively more numerous eastward from Jumpoff Joe thrust accompanied by a decrease in the potassium-feldspar content in the granodiorite. An increase in the same direction of a slight foliation in the granodiorite led Miller and Clark (1975, p. 41) to postulate that:

> ". . . during the later stages of crystallization, when the composition of the remaining melt was similar to that of the dikes, the alkali- and volatile-rich melt was removed from the interstices of the already crystallized material, perhaps by filter pressing. The mobilized melt formed the dikes; thus, the granodiorite is most deficient in potassium feldspar where the dikes are most numerous. The foliate texture results from the collapse accompanying removal of the melt, which forced the micas and remaining melt into interstices between the larger quartz and plagioclase crystals."

The contact of the granodiorite with the country rock has very gentle dips. Numerous roof remnants within the granodiorite crop out just to the west of the trace of the Newport fault. Contact metamorphic effects in the surrounding rock existing far from the surface contact with the pluton combine with the above to suggest that the Phillips Lake Granodiorite underlies much of the region at shallow depth. The Newport fault surface appears to lie at or near the top of this intrusion which I infer to be highly significant in the development of the fault zone and transport of the Newport allochthon. This concept is discussed more fully below along with models of tectonic development of northeastern Washington.

The Silver Point Quartz Monzonite was originally named by Miller (1969) followed by detailed petrographic and petrologic descriptions published later by Miller and Clark (1975). This unit underlies a total of about 380 square kilometers within Newport quadrangles 3 and 4 and the Chewelah-Loon Lake map area (see Figure 6). It essentially is a porphyritic hornblende-biotite quartz monzonite. Miller and Clark describe a distinctive texture of the rock which contains a tri-modal grain size. The potassium-feldspar phenocrysts occur up to 4 cm long surrounded by large crystals of hornblende, biotite, plagioclase and potassium-feldspar averaging 4 mm in size. The groundmass has the same mineralogy with crystal size averaging about 1 mm.

Miller and Clark consider the larger crystals to be earlier crystallization products and postulate that, "Some event, such as rapid loss of heat or volatiles, caused approximately the last 60 percent of the magma to crystallize so rapidly that it could not react with already crystallized minerals." (Miller and Clark, 1975, p. 48). Although several different processes could account for this rapid loss of heat or volatiles, I suggest that shallowing of these plutonic rocks occurred through tectonic unroofing of the batholith by the Newport allochthon. A drop in lithostatic pressure would permit the volatiles within the magma to escape thus promoting nucleation in the remaining melt resulting in smaller crystal size. Drop in pressure on a water-saturated melt might cause the magma to cross the solidus as shown in Figure 7.

Hornblende crystals are aligned sub-parallel with the Newport fault in places where the Silver Point Quartz Monzonite crops out

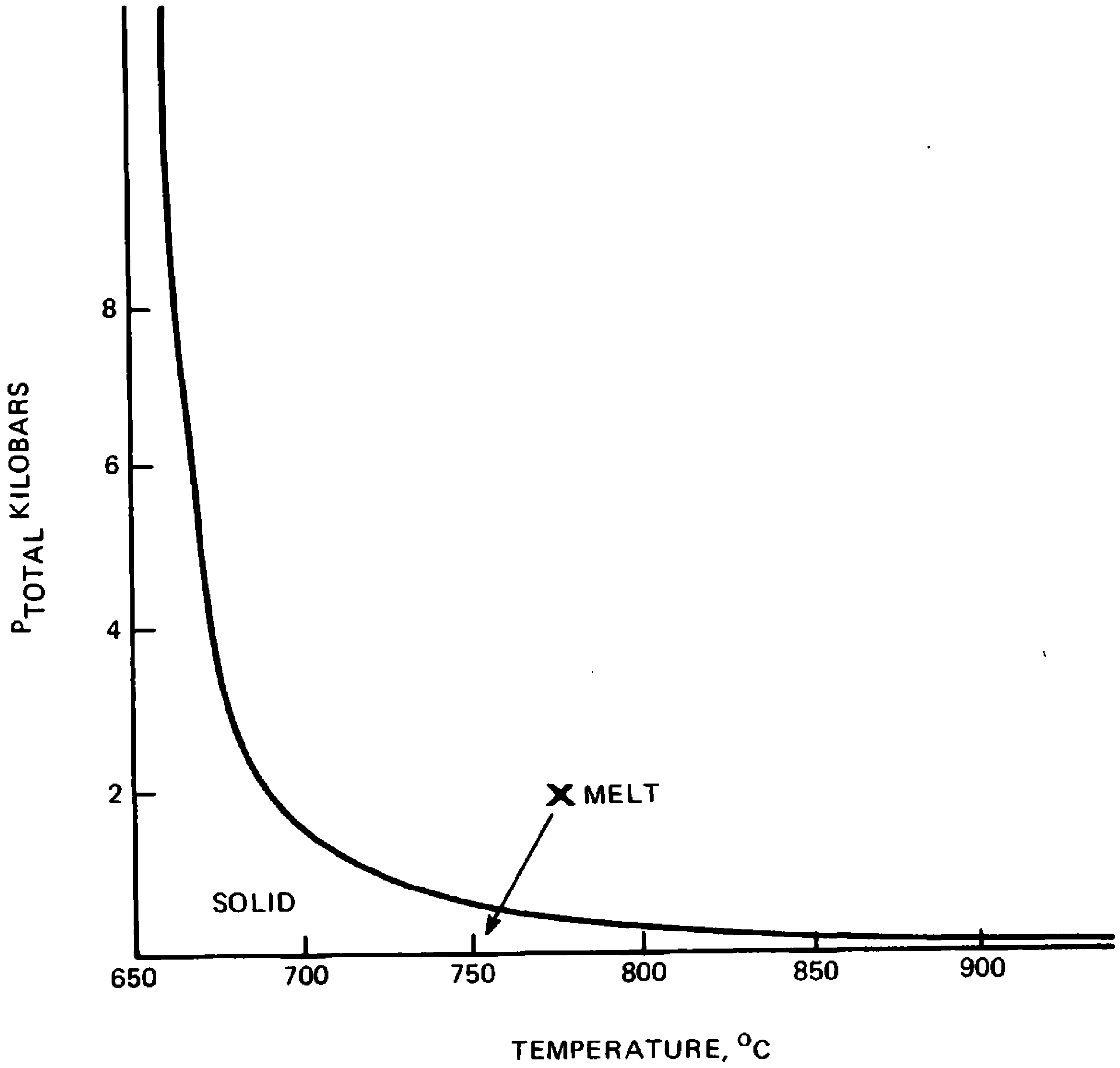


Figure 7. Water-saturated melting curve for granitic liquids showing how a drop in pressure with little or no temperature change may account for crystallization (after Tuttle and Bowen, 1958).

near the fault trace. The proximity of these lineations to the Newport fault zone may suggest that their east-west alignment resulted from movement along the fault but relationships found in good outcrops along Davis Lake suggest differently. Here a complete pluton-border sequence is well exposed in a series of outcrops that show massive plutonic rock (Silver Point) grading into more mafic and foliated rocks of the pluton's margin. The contact of the pluton with the country rocks is somewhat gradational over 40 meters with tongues of plutonic rock and pegmatite extending short distances into the wall rock. Inclusions near the margin of the pluton stretch and align themselves parallel with the intrusive contact as do the long axes of the larger hornblende crystals. The contact of the pluton swings from northeasterly near Davis Lake to nearly east-west before it is cut by the Newport fault (Figure 6). Alignment of hornblende crystals resulted from flow movements in the magma near the plutonic margin and their alignment near the Newport fault is a consequence of the margin trending parallel with the fault in that area.

Potassium-argon dates on hornblende and biotite were determined for three samples of the Silver Point Quartz Monzonite (Engels, 1975; Miller and Engels, 1975). They are:

	SAMPLE		
	1	2	3
Hornblende	51.0 ± 5	46.8 ± 1.7	60 ± 2
Biotite	48.1 ± 1	46.7 ± 1.3	50 ± 1

Kaniksu-Spokane Dome

The Hauser Lake Gneiss and Newman Lake Gneiss (Figure 8) crop out in the southern portion of the Newport no. 4 quadrangle (Miller, 1974), Mount Spokane quadrangle (Weissenborn and Weis, 1976), and the Greenacres quadrangle (Figure 2) where they were first described (Weis, 1968). Foliation within the Hauser Lake Gneiss generally trends north-south and a strong consistent lineation, defined by a streaking of mica and sillimanite within the foliation, plunges 20-40 degrees to the southwest. The Hauser Lake Gneiss may have been derived from the Prichard or Burke Formation of the lower Belt Supergroup (Miller, 1974d; Weissenborn and Weis, 1976).

The Newman Lake Gneiss shows signs of cataclasis and has a penetrative lineation consisting of "streaked out clots of biotite" (Miller, 1974d, p. 3) which plunge variably at low angles to the southwest and lie within a north-south foliation. Miller and Weissenborn and Weis believe that the Newman Lake Gneiss is an orthogneiss.

Cross-cutting relationships within the Newport no. 4 quadrangle place some time constraints on the formation of cataclasis and major faulting in the area. The effects of cataclasis found in the Newman Lake Gneiss are also found within adjacent Cretaceous(?) or Tertiary(?) plutons (TKt and TKl of Miller, 1974d) and presumably represent the same deformation event. The Silver Point Quartz Monzonite cuts Miller's TKl unit and hence is younger. Effects of cataclasis are not found within the Silver Point where the regionally consistent cataclastic foliation is projected along strike northward several kilometers.

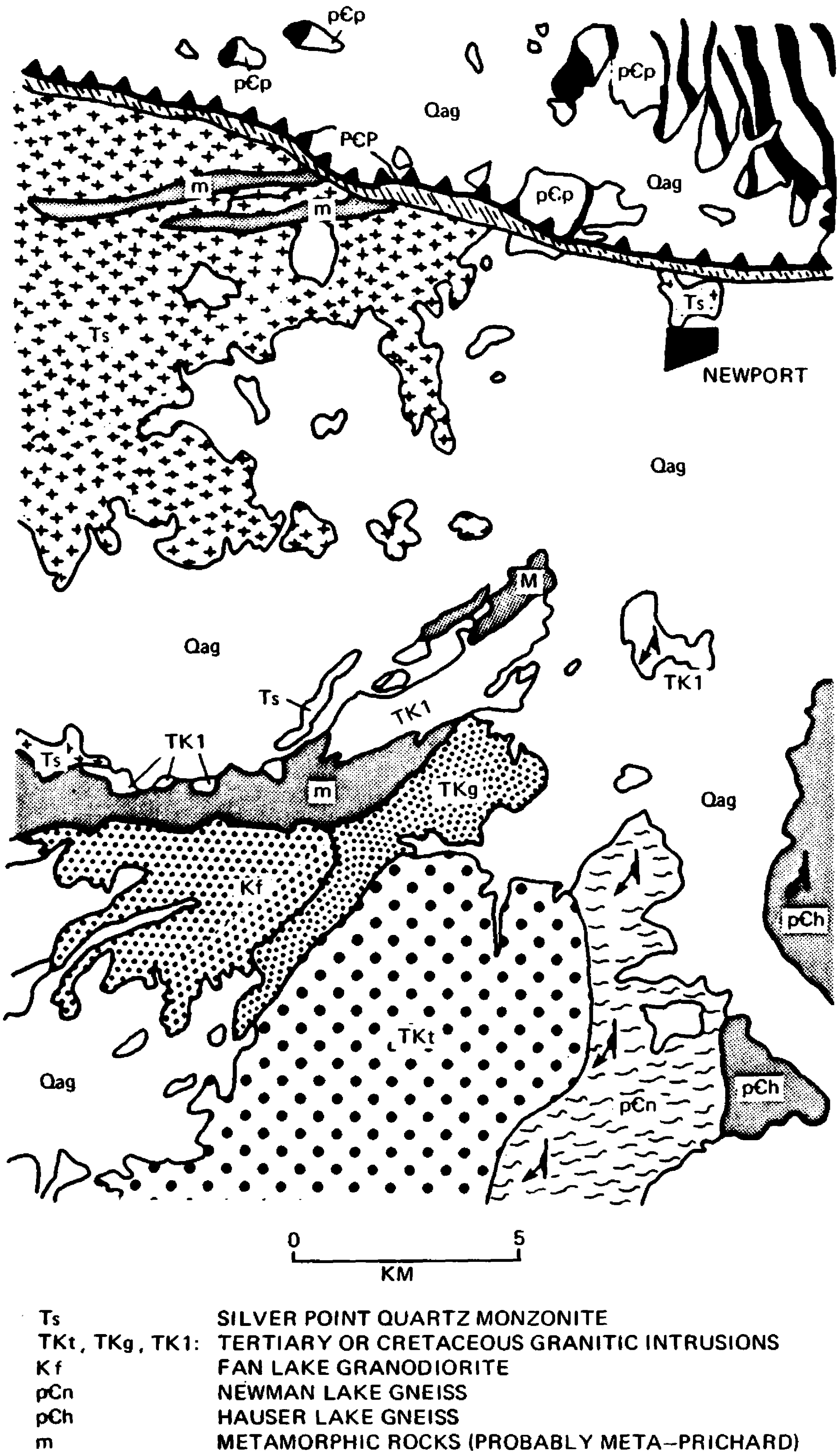


Figure 8. Geology of the Newport Number 4 Quadrangle (from Miller, 1974d).

Since the Newport fault is younger than the Silver Point, the following age relationships are apparent (oldest listed first):

1) intrusion of TKl and TKt
2) metamorphism/cataclasis
3) intrusion of Silver Point Quartz Monzonite
4) transport along Newport fault

Between the town of Priest River and Sandpoint a section of intensely deformed rocks is spectacularly exposed along U.S. Highway 2. These schists and gneisses were mapped by Clark (1964, 1968) as pre-Belt, yet they appear similar to rocks believed to be Prichard elsewhere in the region (Miller, 1974b-d). Folds along this stretch consistently show a transport direction of upper rocks eastward over lower rocks. These folds belong to Clark's first phase of folding and apparently maintain this orientation throughout her study area. She interprets this deformation in terms of a large recumbent fold which she infers on the basis of small-scale structures. Regardless of the existence of such a large fold, these structures may have formed by eastward shearing parallel to the foliation. A second phase of deformation is identified by Clark as consisting of north-south-directed upright, open asymmetric folds.

The Purcell Trench extends from south of Coeur D'Alene Lake northward into British Columbia (Figure 1). The trench has long been believed to be fault controlled (Daly, 1912; Kirkham and Ellis, 1926; Anderson, 1930; Nevin, 1966; Griggs, 1964; Harrison and others, 1972; Miller and Engels, 1975). Miller and Engels (p. 524) present a compelling argument for the location of a major fault or system of faults within the trench in northern Idaho. In support of their argument they point out:

1) the plutonic rock types on each side of the trench are fundamentally different
2) the [regional] metamorphic grade changes markedly across the trench
3) the edge of the zone of discordance coincides with the trench
4) styles of the [radiometric] age contours are different on each side of the trench
5) mylonite and cataclasite are extensively developed within and along the west side of the trench
6) landforms indicate that the west side of the trench may be a fault scarp

The character of the trench appears to change, however, near Kootenay Lake in British Columbia as structures appear continuous across the trench north of this point (Rice, 1941; Fyles 1964, 1967).

Relationships between the suprastructure on the east side of the Purcell Trench and the infrastructure on the west side bear resemblance to relationships found on the eastern margin of the Kettle dome and domes elsewhere in the Cordillera. The details of deformation within the fault zone, however, are unknown because rocks within the trench are poorly exposed. Supracrustal rocks east of the trench may have moved eastward off rocks west of the trench yet this hypothesis is untested and based on somewhat tenuous regional considerations which are explored further below.

CHAPTER III

NEWPORT FAULT

The Newport fault was first mapped and described by Fred Miller while mapping the Newport 30-minute quadrangle for the United States Geologic Survey (Miller, 1971; 1974). Further mapping within the Sandpoint 2° sheet revealed that the U-shaped fault trace extended from near the small village of Tiger on the west to north of Priest Lake on the east. The mapped trace of the fault begins a few kilometers west of Tiger and runs southward along the west side of the Pend Oreille River valley at about the 800 meter elevation. The sinuosity of the fault trace indicates that the fault dips at a low-angle eastward within this part of the valley. Several field measurements of a slight foliation (presumed to parallel the fault surface) within the fault zone confirm the gently-dipping character of the fault. The trace turns easterly near Calispell Lake and runs just north of the town of Newport. It bends northward just north of the town of Priest River and continues up the Priest River valley, along the east side of Priest Lake northward to Continental Mountain near the International Boundary. The fault appears to dip gently westward in the Priest Lake area.

The outcrop pattern of the Newport fault (Miller and Engels, 1975) suggests that rocks of the Newport allochthon belong to a large tectonic plate (i.e. klippe) that moved along the Newport fault. Consequently, the two heretofore unattached ends of the Newport fault trace probably connect and possible locations of the "missing" Newport fault segment are discussed below.

The Newport fault zone consists of cataclastic rock and mylonite. Miller (1974) reports that the zone ranges in width from 125-320 meters and averages about 220 meters. These rocks generally appear greenish-gray in outcrop and upon closer inspection characteristically have no fabric except in those places where a slight and inconsistent foliation is developed. Fractures within the zone appear randomly oriented and are commonly filled with chlorite. The contact of these rocks with those structurally above the fault appears sharp (Miller, 1971) whereas cataclasis decreases gradationally over short distances (about 30 meters) into relatively undeformed rocks lying beneath the sole of the fault. Miller suggests that the granulated material within the fault zone was derived from those rocks beneath the fault. Miller (1971, p. D77-D78) identifies three basic subdivisions within the zone consisting of (moving progressively structurally higher into the zone):

> "1. Plutonic or coarsely crystalline metamorphic rock which contains numerous closely spaced cross-cutting chlorite-filled fractures. Most mafic minerals are altered to chlorite and opaque minerals. Plagioclase composition is similar to that in the unfractured rock, but crystals are broken and twin lamellae are bent. Quartz crystals are broken and strained, and some contain sutured boundaries. This rock grades westward into relatively unfractured plutonic and highly recrystallized metamorphic rock, and eastward into the second subdivision.
>
> 2. Intensely shattered rock showing almost no trace of the original texture. No mafic minerals or forms of mafic minerals remain. Many original plagioclase crystals remain, but are broken and rounded. Most are sericitized, and the composition is more sodic than in the unbroken rock. Quartz is highly broken; most is flattened and contains sutured boundaries. The rock contains thin seams and pods of fine-grained quartz and chlorite.
>
> 3. Mylonite. Dark-green aphanitic rock with scattered fine-grained, internally broken crystals of calcite and plagioclase. Thin sections show a very fine grained mixture of

> quartz, albite, chlorite, calcite and iron oxides. This assemblage appears to have formed from rocks which range in composition from muscovite-biotite quartz monzonite to hornblende-biotite granodiorite. The mylonite and the rock of subdivision 2, above, are generally randomly mixed in the central and upper parts of the fault zone, although the mylonitic rock is more abundant in the upper part."

The purpose of this study was to determine the tectonic transport direction of the Newport allochthon along the Newport fault. The approach I used included the examination of mesoscopic and microscopic fabrics of rocks deformed by movement along the fault. Three areas, all within the Newport 30-minute quadrangle, were chosen for investigation and are shown in Figure 9. Rocks lying well into cataclastic zones typically do not exhibit strong preferred orientations due to mechanical distortions of the grains (White, 1976; Spry, 1969). Most samples were collected from within Miller's first zone or just structurally below it where minerals deformed or growing under conditions of stress would presumably remain unaffected by mechanical disorientation thus preserving any preferred orientations of quartz that might have developed.

Measurements of rock fabric elements such as foliation and lineation were recorded in the field and oriented samples collected for later universal-stage analysis. The orientation of the optic axes (i.e. c-axes) of quartz grains were measured on a Zeiss 4-axis universal stage. Their orientations relative to arbitrary co-ordinates (plane of thin section) were plotted using the lower hemisphere of a Schmidt equal-area net. For diagrams showing statistical anisotropism within the

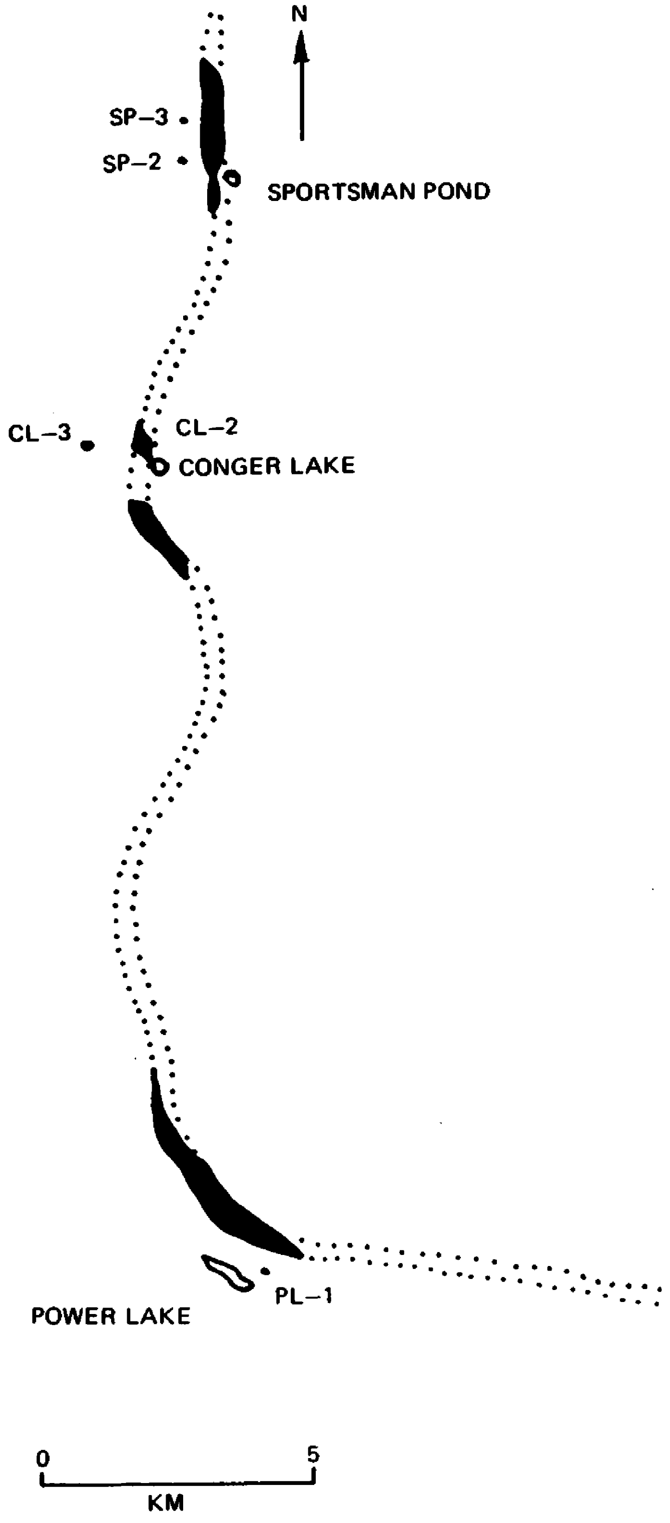


Figure 9. Sample locations along the Newport fault. Shaded areas mark where rocks of the fault zone crop out.

same area, the data was rotated to its original orientation as collected in the field using geographic north-south-east-west as the coordinates of the projection. The data was then contoured per 1% area using the Schmidt or grid method as described by Turner and Weis (p. 61-62, 1963). The symmetry of the quartz fabric and rock fabric were determined and compared as it is of primary significance in kinematic analysis (Paterson and Weiss, 1961). Only those diagrams demonstrating strong preferred orientation were used in the kinematic analysis as it is only in these diagrams where decisions concerning symmetry may be made (Turner and Weis, 1963, p. 64).

Sportsman Pond

Sample SP-2 was collected from along the road northwest of Sportsman Pond within 250 meters of the Newport fault zone (Figure 9). This rock (as well as SP-3) was mapped as Phillips Lake Granodiorite and associated rocks by Miller (1974b). In hand sample, the mica imparts a slight foliation to this rock. It consists of plagioclase, potassium feldspar, quartz, biotite and small amounts of muscovite. Apatite and zircon exist as accessory minerals. Feldspars are generally altered to sericite whereas biotite is almost entirely altered to chlorite. Some of the twin lamellae found in plagioclase are curved and bent. Quartz generally has strongly undulose extinction and well-developed deformation bands. Some quartz grains have Boehm lamellae. Smaller quartz grains apparently are recrystallization products with some grains included within feldspar.

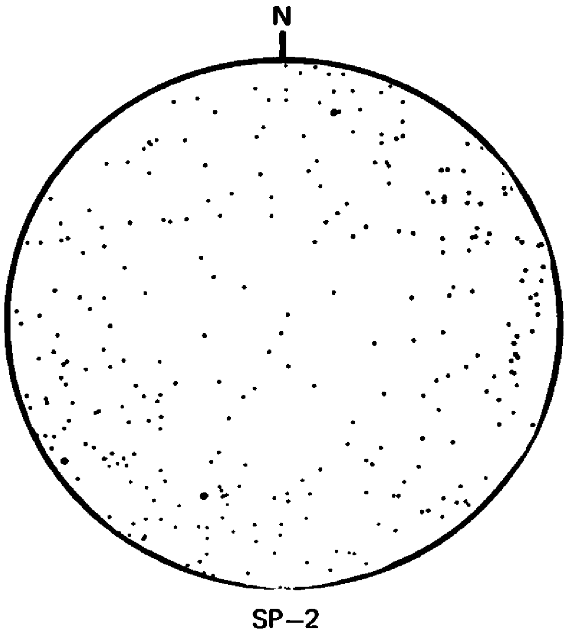
Sample SP-3 was collected about 100 meters from the fault zone contact (Figure 9) and appears massive in hand sample. Plagioclase

(An_{34-36}) is the most abundant mineral in the rock which also contains potassium feldspar, quartz, biotite, small amounts of muscovite and accessory apatite and zircon. Biotite is extensively altered to chlorite and feldspars alter to sericite. Twinning in plagioclase appears slightly bent and in some cases small fractures offset the twins. Quartz has strong undulose extinction and deformation bands.

The orientations of quartz c-axes in these rocks are random (Figure 10). In this area, undeformed rocks below the Newport fault are in sharp contact with thoroughly crushed rocks of the fault zone. The presence of Boehm lamellae in quartz may suggest that some intracrystalline slip may have occurred in sample SP-2 but not enough to produce a preferred orientation of the quartz. It apears that shear movement in the area was confined entirely to the fault zone itself.

Conger Lake

Sample CL-2 was collected from along the northwest side of Conger Lake (Figure 9). Miller (1974b) assigned these rocks to the Phillips Lake Granodiorite and associated rocks. Plagioclase comprises about 45% of the rock with anorthite contents ranging from An_{24} to An_{29}. Twin lamellae are slightly bent in many of the grains. All feldspars are generally sericitized and show weakly undulose extinction. Potassium feldspar in the rock is predominantly microcline and makes up about 10% of the rock. Quartz comprises about 30% of the rock and characteristically occurs in large aggregates containing sutured grain boundaries. It is generally clear and shows strong undulose extinction with deformation bands well-developed. Boehm lamellae are poorly developed in a



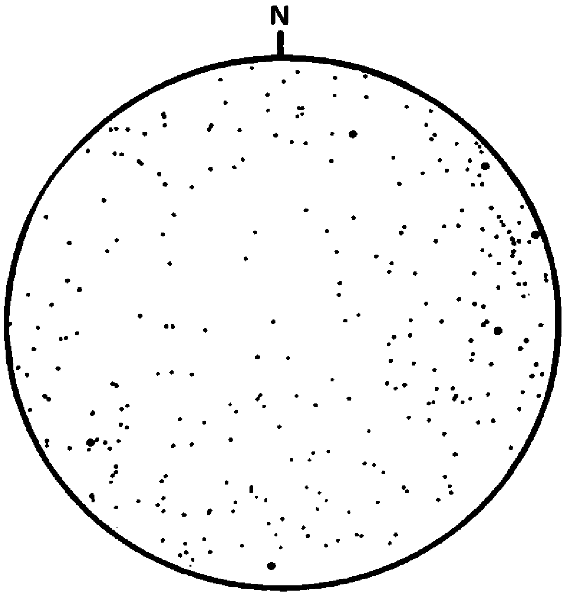
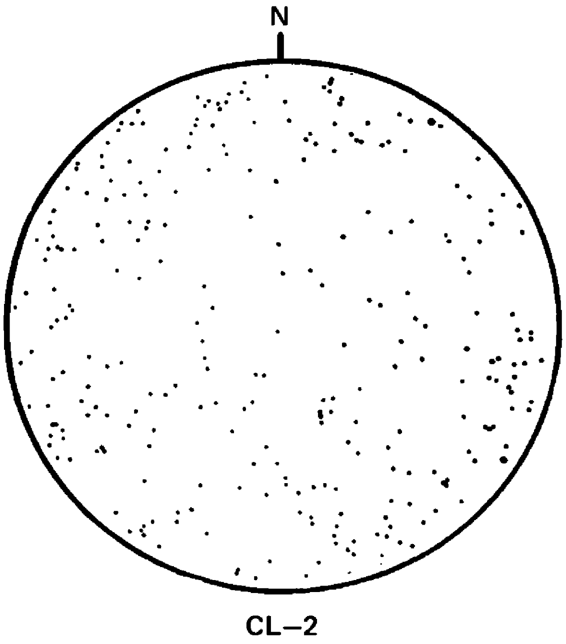


Figure 10. Point diagrams of samples SP-2 and SP-3 showing random orientation of quartz c-axes (larger dot denotes double point).

few grains. Chlorite shows the anomalous "Berlin" blue color and occurs as an alteration product from biotite. Epidote occurs in small amounts with accessory apatite and zircon.

Sample CL-4 was collected from along the ridge northwest of Conger Lake at about the 1000-meter elevation. The rock is a granodiorite assigned to the Phillips Lake Granodiorite by Miller (1974b). In hand sample, the rock is fine-grained and appears weakly foliated. Plagioclase (An_{25-32}) is the dominant mineral constituent and occurs with potassium feldspar, quartz, biotite and accessory epidote, apatite and zircon. Feldspars generally show some alteration to sericite and exhibit mild undulose extinction. Some plagioclase grains have bent twin lamellae and a few are offset along small fractures in the grains. Quartz occurs as individual clear grains and generally has strong undulose extinction with well-developed deformation bands. Biotite characteristically alters to chlorite and generally is oriented subparallel imparting a slight foliation to the rock. Small fractures filled with chlorite extend outward from the mica parallel to this trend and cross grain boundaries.

The quartz c-axes orientation for these two specimens are random as shown in Figure 11. Textures within the two rocks suggest that they have been slightly deformed and the presence of a few Boehm lamellae within CL-2 suggest some intracrystalline gliding may have occurred but not in sufficient amounts to develop a preferred orientation. Several slickenside and mineral lineation measurements taken in the area show that plunges are less than 30° trending N55E - N65E. These rocks,



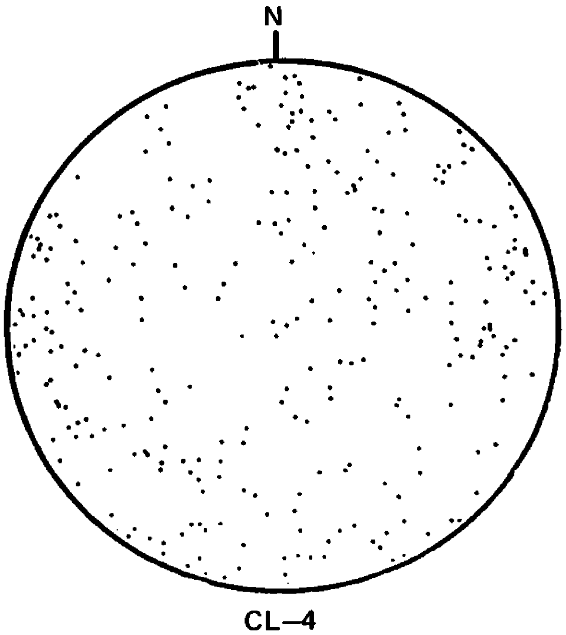


Figure 11. Point diagrams of samples CL-2 and CL-4 showing random orientation of quartz c-axes (larger dot denotes double point).

however, are not deformed severely enough to make any kinematic inferences about transport along the Newport fault.

Power Lake

Sample PL-1 was collected from near the top of the ridge northeast of Power Lake. It is a cataclasite comprised of deformed fine-grained granodiorite containing oligoclase, quartz, potassium feldspar, biotite, muscovite, epidote and accessory apatite and zircon. In hand sample, the rock contains a sub-parallel, closely-spaced and undulatory shear foliation. Undeformed muscovite flakes are clearly seen lying flat on foliation surfaces along with a well-developed mineral lineation (Figure 12). Slickensides lie in the foliation and maintain consistent orientation to the northeast. This consistent orientation is maintained all along Power Lake ridge and in the area northwest of Power Lake (Figure 13). The shear foliation is penetrative at thin section and hand sample scale and is penetrative within a zone at least 40 meters thick on Power Lake ridge. The combination of foliation and lineation defines an orthorhombic fabric symmetry. I infer that the overall fabric was imprinted on these rocks by movement along the Newport fault. The original rock was an unfoliated granodiorite as nearby outcrops of this pluton attest.

Thin-section observation shows large porphyroclasts of feldspar surrounded by a matrix of quartz, feldspar and mica which swirl and wrap around the larger porphyroclasts (Figure 14). Feldspar is generally sericitized, exhibits mild undulose extinction, contains fractures and has bent twin lamellae. Micas lie within the closely-spaced, nearly parallel but intersecting foliation surfaces. Chlorite and sericite

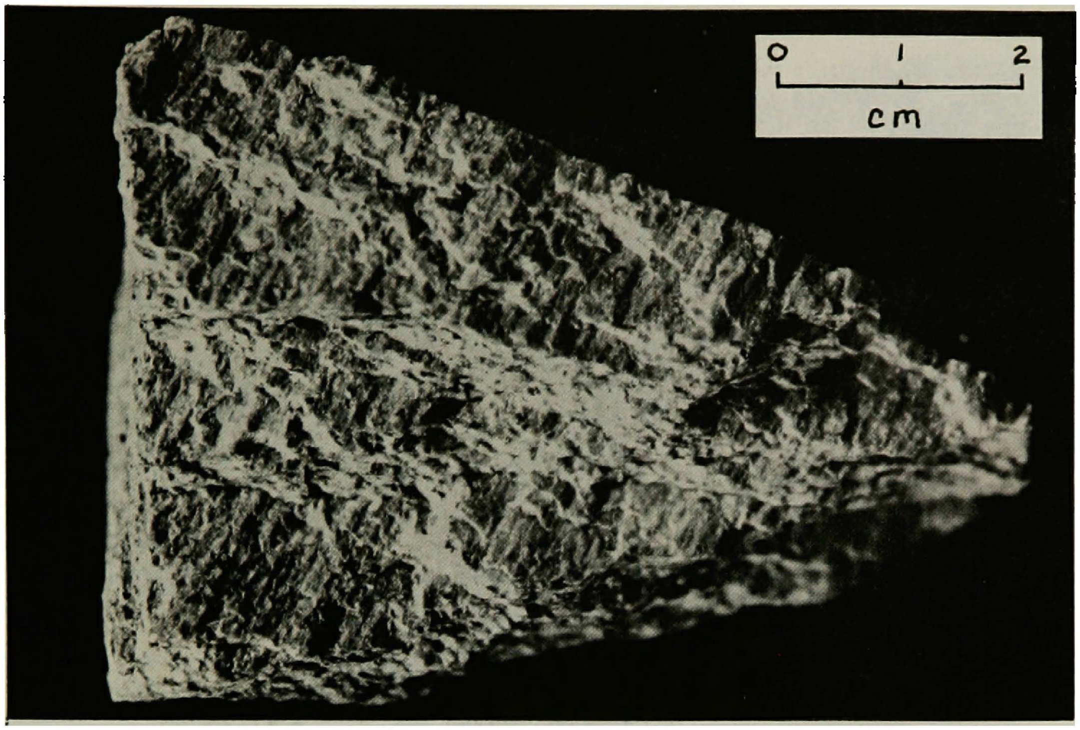


Figure 12. Hand-sample photograph of sheared granodiorite from Power Lake ridge showing mineral lineations and slickensides.

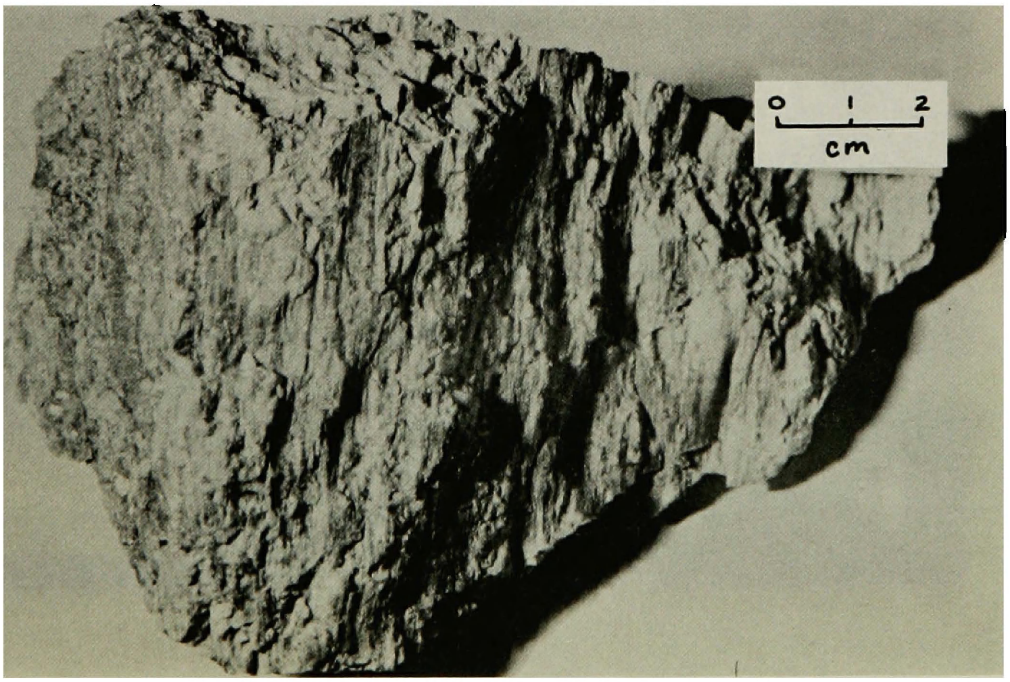


Figure 13. Hand-sample photograph of sheared granite collected northwest of Power Lake showing mineral lineations and slickensides. Note undeformed muscovite flakes lying in the shear foliation.

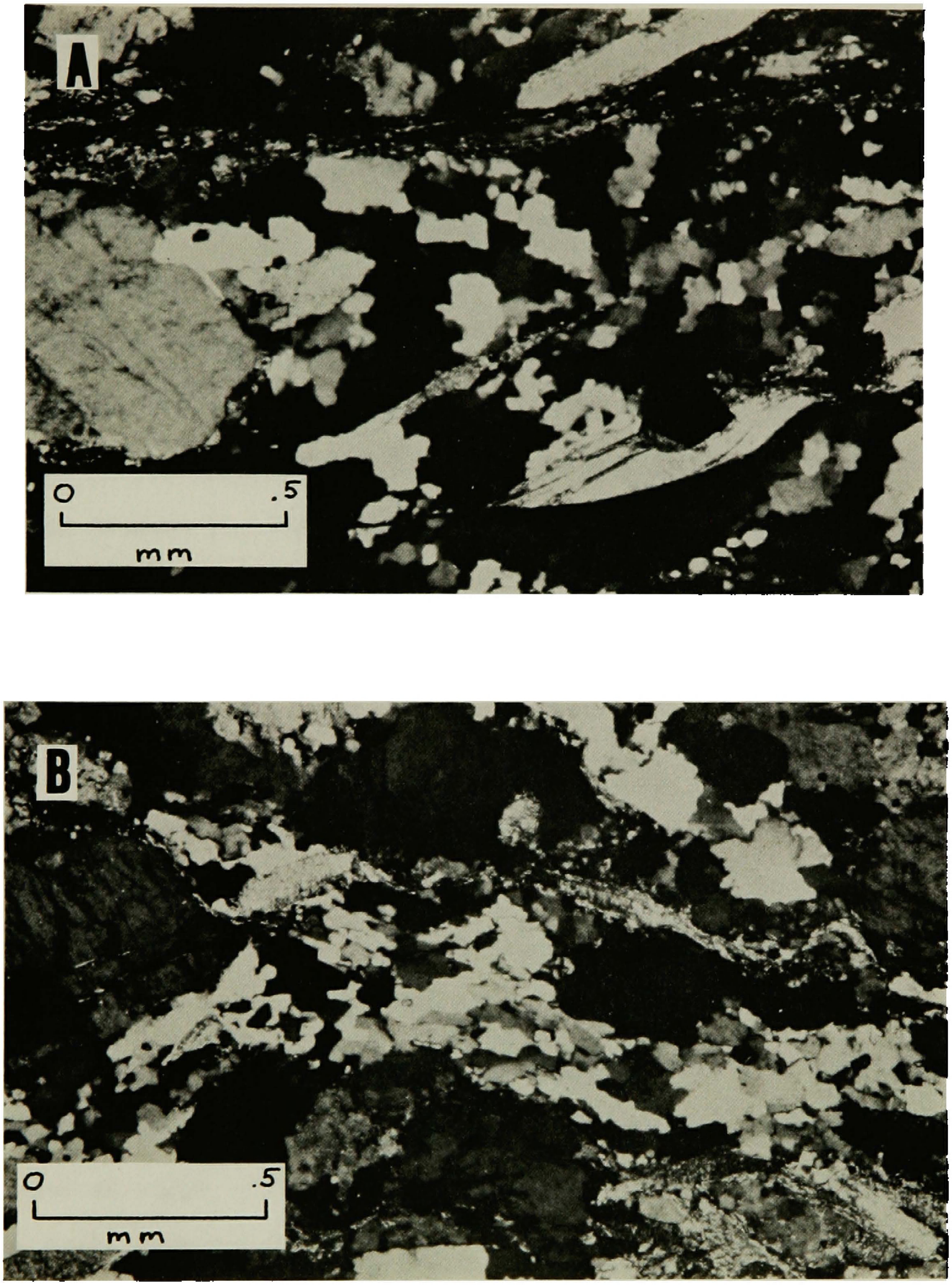


Figure 14. a) Thin-section photograph of sheared granodiorite cut normal to the foliation and lineation.

b) Thin-section photograph of sheared granodiorite cut normal to the foliation and parallel to the lineation.

trail out from larger deformed mica grains along planes of the foliation. Quartz occurs in seams and pods stretched parallel with the foliation. Grains are larger towards the middle of the pods with smaller recrystallized grains more common near the margins. The grains are generally clear, have sutured grain boundaries and generally do not have Boehm lamellae. Deformation bands are present in some grains with most grains exhibiting varying degrees of undulose extinction.

Muscovite generally is undeformed except in some cases where the cleavage traces are mildly bent. Biotite grains normally are smeared-out along foliation planes but a few grains remain relatively undeformed and presumably grew near the end of the shearing event. Small, round, and clear grains of quartz lie at the margins of larger and presumably original quartz grains suggesting that these grains are recrystallization products. This assemblage of minerals suggests that this rock was subjected to at least biotite zone of greenschist facies metamorphism (Hyndman, 1972) during the last stages of shearing.

The quartz sub-fabric diagram is shown in Figure 15. The quartz c-axes form an elongate maximum which may be fit with a girdle normal to the lineation. The c-axis maximum lies at low angle to the foliation and at right angles to the lineation. The quartz fabric symmetry is at least monoclinic and nearly orthorhombic. One of the planes of symmetry nearly coincides with the foliation and two of the planes contain the lineation. Turner and Weiss (1963, p. 253-254) describe this fabric as heterotactic when the foliation does not coincide with a plane of symmetry but since they nearly coincide it may be considered nearly homotactic.

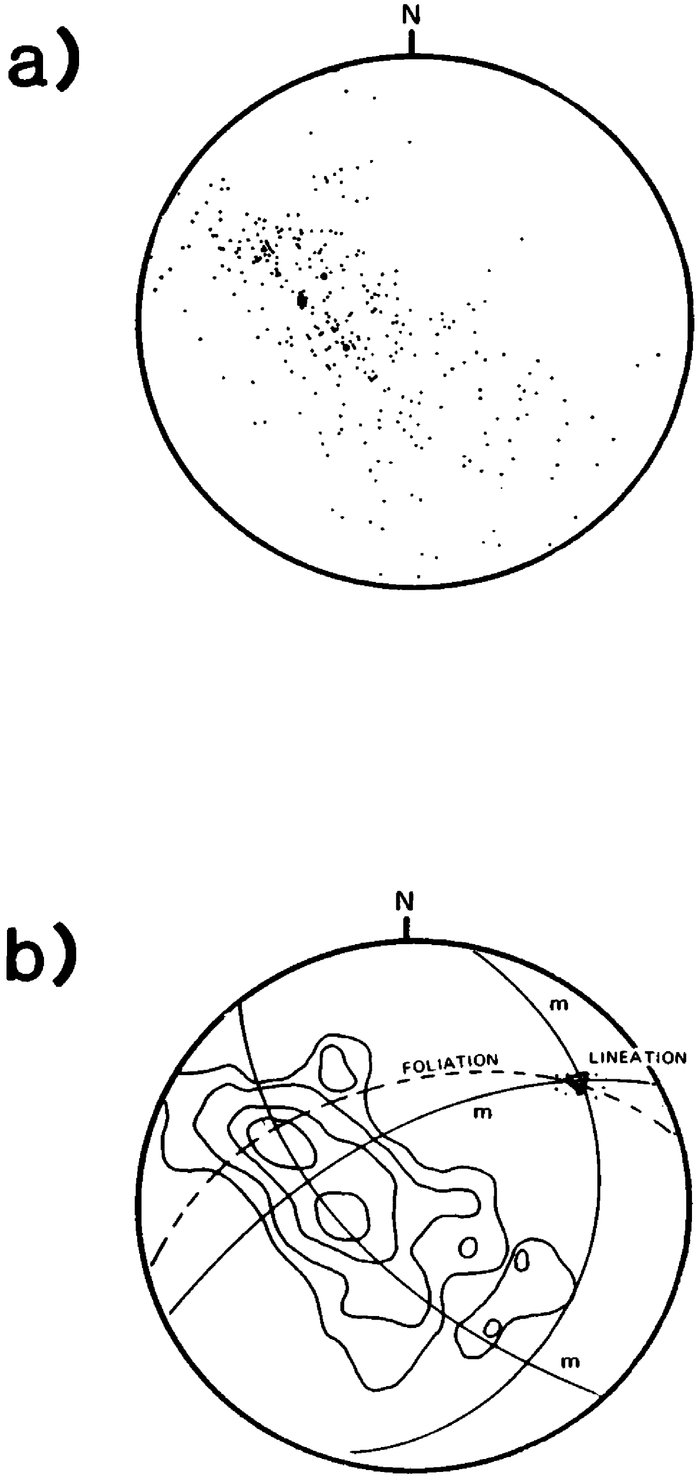


Figure 15. a) Point diagram of sample PL-1 showing quartz c-axes (300 points).

b) Contour diagram of sample PL-1 showing quartz c-axes (300 points). Contours, 1%, 2%, 4%, 6% per 1% area, m = plane of symmetry (larger dot denotes double point, larger dot with + denotes triple point).

An understanding of the mineral lineation and foliation is important in order to make any kinematic interpretation. The mineral lineation consists of elongate feldspar fragments and smeared-out quartz grains. The lineation is parallel to slickensiding on the foliation surfaces; therefore, the lineation is interpreted as plastically stretched grains suggesting extension parallel to the slickensides. The slickensides probably represent latest movement along the foliation under more brittle conditions than those that formed the mineral lineations. Therefore, the foliation is correlated with AB of the strain ellipsoid with the lineation direction inferred to be the A direction.

The overall fabric of the rock directly reflects the movements that produced the structures. The movement picture deduced from the Power Lake samples would be same for a > 40-meter-thick zone of shearing found adjacent to the Newport fault on Power Lake ridge. The movement picture within this zone is correlated with the dominant movement along the Newport fault. This correlation is made because:

1) The intensity of shearing increases near the trace of the fault.
2) Penetrative shear structures of this type are found only near the fault.
3) Shear foliation trends roughly parallel to the trace of the fault.
4) Transport direction parallel to the lineation is in agreement with transport inferred from regional geological considerations.

Deformation of the rocks on Power Lake ridge may be interpreted in terms of simple shear. Deformation is penetrative at all scales on the ridge and persistent lineations suggest a consistent sense of shear. A model of simple shear is consistent with the rock fabric on the grounds of symmetry. Simple shear is monoclinic and the overall fabric of the rocks is at least monoclinic and nearly orthorhombic.

Orthorhombic patterns of quartz optic axes are generally interpreted as flattening deformation normal to the foliation. The development of an orthorhombic pattern, however, does not necessarily demand this interpretation (Eisbacher, 1970; Reikels and Baker, 1977). Turner and Weiss (1963, p. 468) state that "Lineations (a lineations of some writers) lying in the symmetry plane of a monoclinic fabric could on symmetry grounds be identified with directions of greatest differential displacement in the corresponding movement picture." Therefore, based on the above considerations, I suggest that the lineation corresponds to the a kinematic axis and that tectonic transport along the Newport fault was directed northeast-southwest.

Much has been written about quartz deformation and related fabric patterns in the last twenty years, especially in light of numerous experiments on quartz deformation, the resulting preferred orientations and active slip systems. At this time, a number of factors affecting the orientation of quartz have been identified but extrapolation of these results to naturally deformed rocks is still somewhat uncertain (Tullis and others, 1973; Wilson, 1975; Eisbacher, 1970). The preferred orientation of quartz in the Power Lake specimens is discussed in light of inferred movement directions, experimental work and similar quartz patterns reported elsewhere.

A number of glide systems in quartz have been documented within the last 20 years (for example see: Morrison-Smith and others, 1976;

Ave Lallement and Carter, 1971; Christie and others, 1964; Christie and Green, 1964; Carter and others, 1964; Hobbs, 1968; Heard and Carter, 1968). Factors governing development of a particular system of slip planes include temperature, pressure, strain rate, water, quartz content, and stress directions (for example: Ave Lallement and others, 1971; Blacic, 1975; Tullis and others, 1973; Starkey and Cutforth, 1978).

The absence of Boehm lamellae suggest that basal slip is probably unimportant (at least in the latter stages of the quartz deformation) and slip more likely was in a zone containing c since the c-axes form a maximum nearly parallel with the foliation. It would appear that slip would be directed at 90°to c within this zone based on inferred slip directions in the rock but slip may have been accommodated by a combination of movements in variably oriented planes. Therefore, slip was probably prismatic although rhombohedral slip may have been important also (Shelley, 1971; Hobbs, 1968; Wilson, 1975).

The quartz in the Power Lake specimen occurs in pods containing larger original grains and smaller recrystallized grains. Distinction between these grain types was not made when measuring the c-axes yet the strong incomplete girdle maximum suggests that both grain types have similar preferred orientations. To be sure, slip mechanisms, recrystallization and recovery processes all contributed to final orientation of the quartz. Little is known about development of preferred orientations through recrystallization. Lister and Price (1978) report similar quartz fabrics (their Figure 13, α and β grains). Interestingly enough, orientation of original and recrystallized grains does not differ significantly suggesting that dislocation glide dominates the orientation process as Lister and Price suggest.

Quartz girdles forming perpendicular to the lineation and inferred transport direction have been described from numerous locations around the world (see Eisbacher, 1970). A similar pattern to the Power Lake specimen was obtained from the Risfjallet mylonite (Wilson, 1975). Wilson (p. 973) states that ". . . strong maximum close to the foliation are characteristic of upper greenschist or higher grade rocks." He suggests that differences in some c-axis patterns may reflect "differences in the dislocation glide behavior of quartz under different metamorphic conditions." The pattern in the Risfjallet mylonite was obtained from unrecrystallized quartz and hence similarity to the Power Lake specimen supports the hypothesis that dislocation glide is the most important orienting mechanism in quartz-bearing rocks.

Rhodes (1980) describes strong quartz c-axis maxima lying in the foliation normal to the lineation from quartzites lying on the east flank of the Kettle dome. He infers that movement was parallel to the lineation in the rocks and suggests that this type of fabric forms during extreme deformation. Similar quartz orientations reported elsewhere in the Shuswap metamorphic complex (Reesor, 1965) suggest that movements at the margins of these gneiss domes are similar.

Quartz orientation patterns that Eisbacher (1970) reports for mylonitic rocks found along the Cobequid fault zone in Nova Scotia are strikingly similar to the results obtained in this study. He interprets the mineral lineation as flow lines and hence tectonic transport was in the same direction. He reports quartz c-axis girdles lying normal to the lineation and subsequently proposes a movement picture similar to that proposed in this study.

CHAPTER IV

DISCUSSION

Newport Fault

Small-scale structures near Power Lake suggest the Newport allochthon moved to the northeast or to the southwest. Based on several lines of evidence from the regional geology, I infer that tectonic transport along the Newport fault was to the northeast. They are:

1) A similar sequence of rocks lies to the southwest.
2) Dominant movement in the region is from west to east.
3) Window of infrastructure southwest of plate coincides with the southwestern shape of the plate.

The thick package of Belt rocks found in the Chewelah area (see Figure 4) is repeated in the upper plate of the Newport allochthon. Both packages of rocks contain a sequence of Prichard Formation through Paleozoic age rocks. The regional trend is the same in both areas and both dip steeply to the west. Folding, even on a large scale, cannot account for this repeated section and hence juxtaposition probably occurred along the Newport fault. Therefore, it appears that rocks of the Newport allochthon can be matched with rocks they became detached from in the Chewelah area.

An alternative to this model consists of transport of the Newport allochthon eastward from somewhere west of Chewelah. A major problem, however, with this model is one of space. If Belt rocks were to be placed west of Chewelah, Deer Trail rocks would have to be placed back at least that far plus an additional distance to account for net shortening in these rocks. This restoration would place these rocks an unreasonable distance away from any inferred continental margin at the time of deposition. I therefore prefer the simpler model involving much less tectonic transport.

The thickness of the Newport allochthon is not known but some rough estimates may be made from the structural attitude of the fault at the surface. Assuming the Newport fault dips consistently to the east at 30° (which is unlikely) it would presumably lie about 11 km below the center of the allochthon. It is more likely that the fault flattens at depth since it crops out at the eastern end of the allochthon. Therefore a rough estimate of the maximum thickness of the allochthon may be around 6 km. The correlation of rocks and structures above and below the Newport fault is made for the trailing margin of the allochthon which probably was considerably thinner than this maximum estimate. Therefore, this correlation is made assuming that the plate is thin enough in this area such that structures at the surface in the allochthon probably do not vary considerably when they intersect the fault at depth.

Mineral lineations, slickensides and shear foliation are most intensely developed near Power Lake. In other places around the Newport fault, the contact is rather sharp between undeformed rocks structurally below the sole of the fault and thoroughly crushed and broken rocks of the fault zone. The Newport fault surface is probably spoon-shaped as suggested by the gently-plunging synclinal outcrop of the fault trace. According to my model the thickest portion of the Newport allochthon approximately coincides with the center of the plate.

Therefore, as the allochthon moved to the northeast the thickest portion of the plate would have moved across rocks in the Power Lake area. These rocks were deep enough and plastic enough to deform easily whereas thinner portions of the plate would have moved across areas north and east of Power Lake resulting in more shallow-, brittle-style deformation largely confined to the fault zone itself.

If the Newport allochthon is a large klippe, as I believe it is, then the heretofore unattached northern ends of the fault trace should connect. I propose two alternatives concerning the "missing" segment of the Newport fault. First, the trace of the Newport fault may be unrecognized as of yet. The area between the two unattached ends has been mapped in part (Park and Cannon, 1943; Dings and Whitebread, 1965). The Kootenay arc trends northeasterly in this area so movement along the Newport fault to the northeast would presumably result in strike-slip movement along a fault parallel to the trends of the arc. Such a fault would be difficult to locate in this area since offset of major structures and bedding contacts would probably be small or absent. Extensive forest cover and glacial deposits in this area complicate field observation.

A second alternative would be that the remaining section has been truncated by a northeast-trending normal fault and removed by erosion. High-angle faults in the area, however, are downthrown on the northwest (see Park and Cannon, 1943) which presumably is the reverse of that which would be expected if the above were true. These two alternatives are speculative, of course, but further study in the area is needed to test them.

Interpretations concerning direction and amount of transport along the Newport fault lead to speculation about the mechanism of transport. There are essentially two schools of thought about transport mechanisms in the Cordillera: push from the west and gravitational sliding. Push from the west may be broken down into sub-categories based on the origin of the eastward compression but only the general concept will be considered and discussed here.

Northeasterly transport of the Newport allochthon represents anomalous movement in northeastern Washington where most movement apparently was to the east or southeast. Structures in the Kootenay arc in this area trend northeasterly and suggest transport to the southeast. Therefore, the forces that produced movement within the Kootenay arc would not have directly produced northeastward transport of the Newport allochthon. Lineations within the Kettle dome suggest that large movements were to the east. Cataclastic lineation within the Newman Lake gneiss and surrounding rocks suggests that transport was directed northeast-southwest. It has been shown above, however, that this deformation preceded transport along the Newport fault, hence those forces are probably unrelated to transport along the Newport fault. The above considerations are certainly not conclusive yet are suggestive that eastward compression probably did not directly produce transport along the Newport fault.

I propose that transport along the Newport fault was predominantly controlled by gravitational sliding downslope from the Chewelah area. A model of gravity glide accounts for the locally northeastward transport direction of the Newport allochthon and for textures in the Silver Point Quartz Monzonite.

Several mechanisms of gravitational sliding have been proposed but the mechanism proposed by Kehle (1970) is probably most applicable here. Kehle (p. 1642) states that "...deformation occurs in a manner best described as viscous deformation and that almost all such deformation concentrates in the lowest viscosity strata." The Newport fault cuts steeply dipping Belt rocks at a high angle and hence is not a bedding fault which often forms during thrusting in the Cordillera. In the absence of low-viscosity lithologic layers, I believe that the location of the Newport fault is controlled by a structural zone with lower shear strength. It appears in this case that the Newport allochthon became decoupled from lower rocks near the intrusive contact of plutons. Two plutons, the Phillips Lake Granodiorite and the Silver Point Quartz Monzonite, were instrumental in the development of the Newport fault.

As noted above, the Newport fault apparently lies near the top of the Phillips Lake Granodiorite. The intrusive contact is sub-parallel to the fault in the southern reaches of the pluton and approximately coincides with the position of the fault. The locally planar fabric of the pluton near its margin as well as the subhorizontal attitude of the intrusive contact presumably produced a zone of reduced shear strength parallel to the regional stress and hence deformation preferentially concentrated here as Kehle's principle dictates. Even if the rock was already crystallized, this zone had conditions favorable for sliding. Evidence for plastic-style shearing and at least upper greenschist facies metamorphism around Power Lake suggests a deep environment which favors development of a zone of shear (Kehle, 1970). Metamorphic reactions producing water may have aided shearing along this zone.

The Newport fault surface also appears to coincide closely with the intrusive contact of the Silver Point Quartz Monzonite west of the town of Newport. Brittle-style deformation near the fault zone within the Silver Point pluton suggests the rock was completely solidified when the last stages of movement occurred. Tri-modal grain size within the pluton may suggest that the rock was only partially crystallized when sliding was initiated. Intrusion of the Silver Point magma would have greatly reduced regional shear strength and in turn resulted in gravitational transport downslope of the overlying rocks. The magma would crystallize progressively as sliding progressed due to a drop in pressure. Movement would continue along this zone of shear because it was weak but the Silver Point probably was solid for the latter part of the time that sliding occurred.

The model proposed here resembles a model proposed by Gastil (1979) where decoupling takes place between supracrustal rocks and diapiric plutons of the infrastructure. The cover rocks slide away as the area above the plutons rise isostatically. Similar mechanisms which reduce regional detachment shear strength have been proposed by Hyndman (1980) and Scholten (1973).

Transport along the Newport fault most likely occurred during Eocene time. Age dates on the Silver Point Quartz Monzonite are Eocene. The Newport fault cuts the Silver Point pluton and therefore is younger. These dates probably represent emplacement because the

Silver Point was not affected by the presumably Late Cretaceous deformational event which affected the Newman Lake gneiss and surrounding rocks. The relationships within the Newport no. 4 quadrangle which are discussed above, indicate that intrusion of the Silver Point was post-Cretaceous.

The Pend Oreille Andesite is found only in the southwestern portion of the Newport allochthon. Flows of this unit contain phenocrysts of hornblende and biotite which have K-Ar age dates of 51.0 m.y. and 50.4 m.y. respectively (Pearson and Obradovich, 1977). I believe these volcanics were derived from the Silver Point Quartz Monzonite based on three considerations. First, its present location on the trailing margin of the Newport allochthon is that which would be expected if any volatile-rich magma was vented as a result of initial unloading of the Newport allochthon off the top of the Silver Point pluton.

Secondly, mineralogy of the Pend Oreille Andesite is similar to that of the Silver Point. Biotite and hornblende phenocrysts in the Pend Oreille Andesite probably represent minerals which crystallized early in the magma chamber before extrusion. The Silver Point pluton also contains large hornblende and biotite crystals which apparently crystallized early. Thirdly, K-Ar age date determinations of hornblende and biotite from the Silver Point are roughly equivalent to those of the Pend Oreille Andesite.

The Newport fault may cut conglomerates of the Tiger Formation since they are confined exclusively to the upper plate of the Newport allochthon but field relations do not provide any conclusive proof that this is the case. The Tiger Formation lies conformably on the Pend

Oreille Andesite and therefore probably was syntectonic to transport along the Newport fault. Syntectonic conglomerates are common throughout the Cordilleran thrust belt.

Relationships between Low-Angle Faults

Little is known concerning transport along low-angle faults in northeastern Washington and any relationship between them at depth can only be inferred. In the following discussion, possible relationships between these faults are considered in light of the regional geology discussed in Chapter II. Construction of generalized cross-sections across northeastern Washington aid in the formulation of several general models explaining the development of these low-angle faults. Some aspects of the cross-sections remain the same from model to model which reflect my personal bias. I should stress that these models are somewhat speculative and do not represent all possible models but may provide a starting point from which to build.

It is argued above that mylonitic and cataclastic rocks of the Kettle dome and Okanogan dome represent gravity-induced detachment zones probably of Cretaceous age. Perhaps a thrust surface of regional extent lies below these domes in similar fashion to the southern Appalachians. Here high-grade and crystalline Precambrian and Paleozoic rocks have been thrust at least 260 km westward over flat-lying, autochthonous, lower Paleozoic sedimentary rocks (Cook and others, 1979). No direct evidence is available for such a surface in northeastern Washington but such a possibility should not be ignored.

When the Newport allochthon is placed back in its original location in the Chewelah area, the western edge of the upper plate coincides with the Jumpoff Joe fault. This leads to speculation whether the Newport fault is an extension of the Jumpoff Joe fault or whether this relationship is fortuitous. An alternative explanation would be that movement along the Jumpoff Joe fault gave the impetus that initiated gravitational sliding out ahead of the eastward-moving, detached suprastructure. If this is true then the Jumpoff Joe fault may have been reactivated in Tertiary time as a result of further movement off the Kettle dome along the Kettle River fault.

The shear zone in the Newman Lake gneiss and surrounding rocks may represent the same regional detachment surface found at the margin of the Kettle dome (Figure 16). Alternatively it may be a deeper detachment surface which possibly underlies the Kettle and Okanogan domes (Figure 17). The Newman Lake shear zone most likely is the west-dipping extension of the fault found in the Purcell Trench. Transport directions in the Kettle dome shear zone and within the Newman Lake shear zone are different; thus movements along the faults most likely occurred independently of the other. White (1978) proposes that gravitationally-controlled movement best explains differences in transport directions along thrust faults in northwestern Montana. Therefore, gravity probably controlled movement along these surfaces leading to removal of supracrustal rocks off the Kaniksu-Spokane dome.

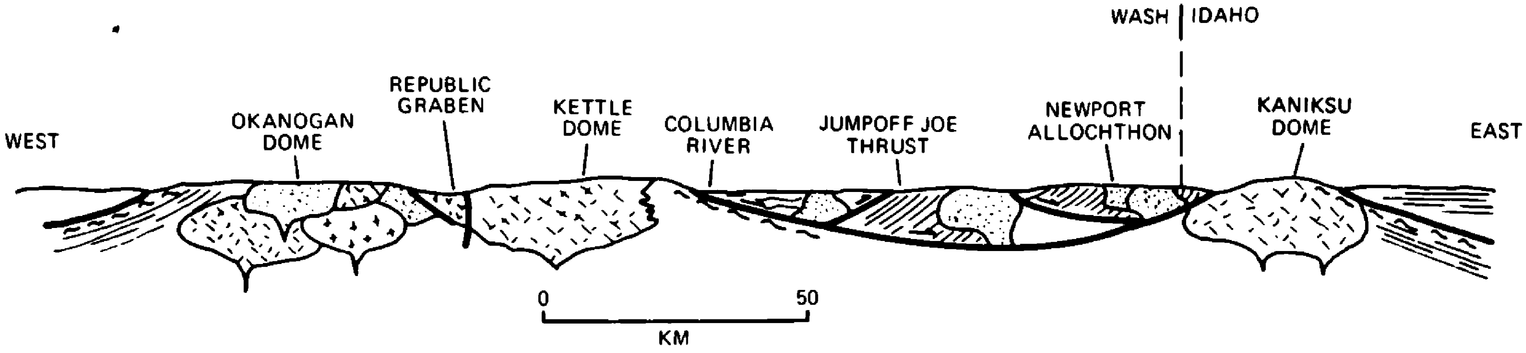


Figure 16. Cross-section model showing low-angle faulting without regional detachment at depth beneath Kettle and Okanogan domes.

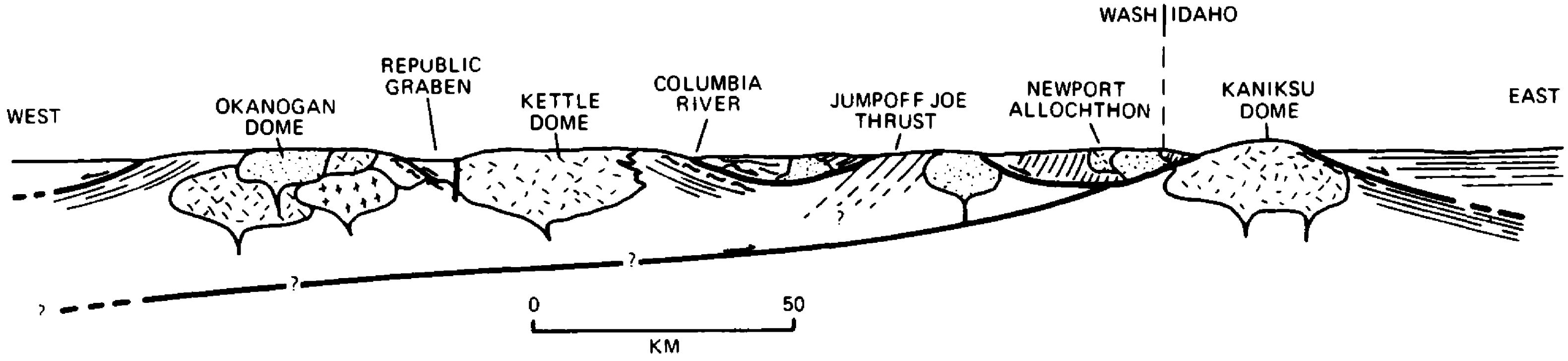


Figure 17. Generalized cross-section northeastern Washington and northern Idaho modeling relationships of low-angle faults including the presence of a hypothetical regional detachment at depth.

CHAPTER V

SUMMARY AND CONCLUSIONS

Mineral lineations and slickensides in the Power Lake area (see Figure 9) demonstrate that transport along the low-angle Newport fault was to the northeast. Transport took place in the Tertiary Period (Eocene?) under at least greenschist facies metamorphism. Quartz fabrics of rocks obtained near the fault are at least monoclinic and nearly orthorhombic with elongate maxima lying at low angles to the foliation and normal to the extension direction.

It appears that the Newport allochthon originated in the Chewelah area southwest of the study area based on correlation of rocks and structures above and below the fault. The Newport fault's position near the top of two plutons in the area suggests a cause/effect relationship where at least one of these plutons was semi-consolidated thereby reducing regional shear strength and promoting gravitational transport to the northeast. Shearing associated with transport along the Newport fault appears most intense in the Power Lake area because the greatest thickness of the allochthon moved across that area. Transport of the Newport allochthon most likely occurred in Eocene time because (1) the fault may cut an Eocene conglomerate (2) the fault cuts a pluton on which Eocene K-Ar age dates have been obtained (3) Eocene volcanics are confined to the upper plate (4) transport along the Newport fault postdates a presumably Cretaceous deformational and intrusive event.

Low-angle detachment faulting in northeastern Washington had a profound effect on the tectonic development of the area. High-grade regional metamorphism culminated in the Cretaceous Period along with gravitational detachment of the suprastructure from the infrastructure. The leading edge of rocks which moved eastward off the top of the Kettle dome area may be delineated by the Jumpoff Joe thrust near Chewelah. Transport along the Newport fault was to the northeast and presumably later than this episode of detachment although renewed movement along the Kettle River fault and the Jumpoff Joe thrust in the Eocene may have initiated detachment of the Newport allochthon in the Chewelah area.

It can only be speculated at this time whether the Newman Lake shear zone is related to detachment in the Kettle dome area or represents a deeper thrust surface lying beneath the Kettle and Okanogan domes. This west-dipping shear zone appears to flatten between the town of Priest River and Sandpoint where rocks contain structures suggestive of eastward shearing parallel to the foliation. The Purcell Trench may represent the east-dipping analog to this surface along which rocks east of the trench moved off the top of the Kaniksu-Spokane dome. Of course, these regional relationships between the low-angle faults are speculative and hopefully further work in the region will clarify them.

APPENDIX

Proposed Genetic Models for the Kettle and Okanogan Domes

Donnelly (1978) recognizes the structural and petrologic similarity of the Kettle dome to domes of the Shuswap terrane. Based on those similarities he considers the Kettle dome to have formed in the same manner as that proposed for the Shuswap domes which are discussed below (see Reesor, 1970).

Preto (1970) working in the Grand Forks map-area just across the International Boundary suggests a mechanism or sequence of deformation similar to that suggested by Reesor. Metamorphic foliation and emplacement of granitic rocks developed during a period when regional stresses caused movement parallel to the stratification in the rocks. Deformation proceeded with development of north-verging, east-west-trending folds followed by upward movement of the migmatitic core creating the northward trend of doming in the rocks. Subsequent activity included retrograde metamorphism and potash metamorphism followed later by intrusion of granitic rocks on which Eocene and Oligocene radiometric dates have been obtained.

Rhodes (1980, p. 88) suggests the following sequence of tectonic events which formed the Kettle dome:

(1) Middle to Late Mesozoic(?) amphibolite facies metamorphism coincident with distributed thrusting which in the latter stages involved mylonitization at shallow structural levels.

(2) Middle Tertiary(?) regional doming.

(3) Middle Tertiary(?) low-angle faulting along the margin of the dome coeval with local brecciation and retrograde metamorphism.

(4) Post-Eocene eastward gravity sliding and associated high-angle faulting of the cover rocks.

Cheney (1980, p. 464) proposes that the Kettle dome is not a gneiss dome but rather "the gently upwarped basement of Precambrian(?) metamorphic rocks". The term gneiss dome may be applied to these rocks as long as it carries no genetic significance other than defining the structural attitude of the gneisses.

Cheney considers that northeastern Washington is dominated by large-scale, north-northeasterly-trending Tertiary folds and that the Kettle dome is one of the anticlines comprising this terrane. According to his model, doming occurred during a period of post-Eocene folding. Widespread cataclasis and thrusting was largely synchronous with this episode of deformation. He suggests that the cataclastic zones may represent zones of decoupling between batholithic and metamorphic terranes, and the overlying sedimentary pile and considers the possibility that the low-angle faults and cataclastic zones are part of a regional folded Tertiary thrust.

Waters and Krauskopf (1941) attributed the origin of the mylonites and gneisses of the dome to the rise of a partially crystallized magma. The regionally metamorphosed wall rocks became crushed and broken whereas the border zone became mylonitized as the magma continued to rise. They postulate that the wall rocks show no effects of contact metamorphism due to the insulating properties of the more rigid border zone of the batholith. Therefore they suggest that the mylonites and gneisses are protoclastic and did not form during regional metamorphism.

Snook (1965) later, however, contended that the gneisses were, in fact, formed during regional metamorphism of a sedimentary and volcanic terrane. The upper levels of the gneiss were later sheared and mylonitized along subhorizontal planes under low temperatures and in a dry environment. He concludes that the mylonite zone now exposed at the western edge of the dome resulted from a distributed flat thrust near the top of the gneiss body. The entire mass was later folded and arched with subsequent high-angle faulting along the western and southern borders of the area.

Another model of formation of the Okanogan dome has been presented recently by Fox and others (1976). They agree with both Snook (1965) and Waters and Krauskopf (1941) that the Tonasket Gneiss fringing the dome at the western margin is of metasedimentary and metavolcanic parentage. As Waters and Krauskopf suggested, they believe that the granitoid gneiss which comprises a large part of the dome is probably of igneous origin and that the internal penetrative deformation developed with emplacement of the mass. They therefore conclude that the gneiss dome formed by regional metamorphism of a sedimentary and volcanic terrane at great depth which "culminated in the mobilization and diapiric emplacement of the dome" (Fox and others, 1976, p. 1220). They also suggest that the gradual transition from granitoid gneiss eastward into almost structureless granodiorite and associated satellitic dikes indicates that this part of the dome was molten.

Proposed Genetic Models for other Cordilleran Gneiss Domes

Other gneiss domes within the Cordilleran region include those lying within the Shuswap metamorphic complex in British Columbia (Reesor, 1965, 1970; Hyndman, 1968; McMillan, 1970; Reesor and Moore, 1971). Structures within these domes are similar to those in the Kettle and Okanogan domes. Rocks within the domes characteristically consist of a core-zone of migmatitic and granitoid rocks. Supracrustal rocks comprised of low-grade metasediments are separated from the rocks of the domal infrastructure by a zone of shearing and cataclasis on the east yet the contact is gradational on the western margins of the dome. This asymmetry is also marked by the eastward increase in the intensity of streaking lineation and also in the amount of flattening and elongation of quartz and feldspar aggregates.

Reesor (1970) conceives dome formation in the Shuswap beginning with a north-northwesterly trending zone of high heat rise leading to migmatization and high-grade metamorphism accompanied by large-scale folding. These northward-verging, east-west folds permitted rise of migmatite and granite gneiss beneath the folds resulting in localized diapiric emplacement within the folded mantling rocks. This rise was synchronous with formation of a northwest-trending arch along the eastern portion of the complex. In general, then, the association of a migmatitic and gneissic core zone within a contrasting mantling zone consisting of metasedimentary gneisses resulted from contrasting rock sequences reacting differently to metamorphism and deformation. Recently, some consider rocks of the core zone to be part of a remobilized Precambrian basement (Wanless and Reesor, 1975; Duncan, 1978).

The Rincon Mountains in Arizona comprise another gneiss-dome complex lying within the Cordillera (Davis, 1975). Granitic gneiss and granite of Precambrian age form the core of the dome. At the top of these rocks lies the Catalina fault which parallels the attitude of the foliation in the gneiss. Structural analysis of fold arrays around the complex produce slip-line directions radially centered on the Rincon Mountains. Davis concludes that diapiric rise of the gneiss and granite domed the cover rocks and initiated gravitationally controlled sliding of the Paleozoic and Mesozoic age rocks of the suprastructure along the surface of the Catalina fault.

Davis and Coney (1979) propose that metamorphic core complexes in the Cordillera formed during a time of regional extension and thermal activity. Their model is compared to that of formation of megaboudinage where crystalline infrastructure neck, arch and fault developing zones of penetrative foliation, lineation and also, in places, mylonite. The movement of the basement rocks is not translated across the unconformity into the supracrustal rocks but rather the cover rocks become detached and gravitationally move down dip along the decollement zone resulting in a deformational style of folding of the sediments independent from that in the infrastructure. This results in tectonic denudation of the dome and a cessation of metamorphic activity within the complex.

The Bitterroot dome in western Montana is a well-developed example of a plutonic-core gneiss-dome complex (Hyndman and others, 1975; Hyndman, 1980). Rocks of the infrastructure include granites of the Bitterroot lobe of the Idaho batholith and associated regionally metamorphosed paragneisses. The transition from these rocks into low-grade rocks of the suprastructure is gradational on the northern edge of the dome whereas they are separated on the east by a 100 km long zone of cataclasis and mylonite. To the east of this zone lies the Sapphire tectonic block 100 km long and 70 km wide, which coincides with the dimensions of the dome. It consists largely of low-grade Belt metasediments and includes Paleozoic and Mesozoic age rocks near its eastern margin. Rocks of the infrastructure have a penetrative cataclastic foliation containing a penetrative, unidirectional mineral streaking and slickenside lineation which is most strongly developed on the eastern margin of the dome and gradually dies out westward across the dome. The dome formed in isostatic response to gravitational detachment of the Sapphire tectonic block 75 or 80 million years ago. The consistent trend of lineations indicates denudation of the dome in a unidirectional and not radial manner. Hyndman suggests that the asymmetry in the intensity of lineation and foliation development formed because the greatest thickness of the block passed only over the eastern portion of the present-day dome. This model is in contrast to the megaboudinage theory in that denudation precedes and causes rise of the dome.

Republic Graben

The Republic graben is the dominant structural feature lying between the Kettle and Okanogan domes. The term graben is used here although the nature of this structural depression is in debate (Cheney, 1980).

Several workers have mapped and described the graben in some detail (Parker and Calkins, 1964; Muessig, 1967; Staatz, 1964). The graben extends from the International Boundary southward to the Columbia River where it disappears under the Columbia Plateau basalts. It is bounded on the southeast by the Sherman fault which trends N12E and extends across the border into Canada. Two faults define the western border of the graben: the Bacon Creek fault on the north and the Scatter Creek fault zone to the south. The graben ranges from 11 to 17 km in width. The amount of displacement on the Sherman fault has been estimated to be on the order of thousands of meters of dip-slip movement (Muessig, 1967). Muessig estimates at least 6 km of normal movement along the Bacon Creek fault. He considers offset across the Scatter Creek fault zone farther south to be of the same order.

Rocks within the Republic graben range in age from probable late Paleozoic to Recent. Schists, phyllites and marbles, probably of Permian age, comprise the oldest exposed rocks. Greenstone underlies these metamorphosed sedimentary rocks in the northern part of the graben. The O'Brien Creek Formation (53 m.y. - Pearson and Obradovich, 1977) forms the basal Tertiary unit lying with angular unconformity on older rocks and consists of mainly volcaniclastic units. The Sanpoil volcanics overlie the O'Brien Creek Formation and consist of rhyodacitic lavas and breccias. These rocks and their correlatives throughout northeastern Washington have K-Ar dates of approximately 41 million years (Pearson and Obradovich, 1977). The Klondike Mountain Formation unconformably overlies the Sanpoil and consists of a basal tuffaceous deposit overlain by flows, breccias and domes of intermediate composition. Pearson and Obradovich infer the basal Klondike to be about 46 million years old.

The graben contains numerous faults which tend to be straight and dip steeply (Parker and Calkins, 1964; Staatz, 1964; Muessig, 1967). They trend roughly parallel to faults comprising the border of the graben although there are some faults which trend normal to the trend of the graben. A thrust fault of large displacement, the Lambert Creek thrust, is located in the northeastern part of the graben. Thrusting occurred before latest movement on the graben faults and hence before deposition of the middle member of the Klondike Mountain Formation (Muessig, 1967).

The outcrop patterns of the formations in the southern half of the graben delineates a large-scale fold named the Sanpoil syncline by Muessig. The fold extends from just north of Republic southward through the Bald Knob quadrangle mapped by Staatz (1964). The west limb of the fold generally dips gently east whereas the east limb tends to dip more steeply and in some places is overturned to the west. Rocks belonging to the middle member of the Klondike appear to have been folded with formation of the syncline.

Subsidence of the Republic graben occurred over a considerable period of time during early and middle Tertiary time. Staatz (1964) suggests that graben formation began when small rifts formed in a structurally weak zone. Rocks of the O'Brien Creek Formation were deposited as an irregular blanket across the region shortly thereafter. Muessig (1967) suggests that Tertiary deposits were laid down in local basins and valleys. It appears that the rocks were progressively deformed while the graben subsided as suggested by several angular unconformities within the graben. Muessig believes that subsidence and deposition were interrupted periodically by compression not confined to the graben and thus considers that folds such as the Sanpoil syncline were not generated by graben subsidence. Staatz suggests that sinking of the graben commenced soon after extrusion of the Sanpoil volcanics and continued as the volcanics were deposited. The faults bounding the graben may have acted as conduits for the ascending magma. The sinking of the block may have been aided by the weight of the extruding volcanics and the block possibly sank into the void left by the escaping magma. Latest movement along faults bounding the Republic graben appears to have taken place during or shortly after deposition of the Klondike Mountain Formation in Miocene time (Parker and Calkins, 1964; Muessig, 1967; Staatz, 1964).

Cheney (1980) proposes a model quite contrary to those suggested above. He points out that the Tertiary formations in the Republic graben are also found across northeastern Washington displaying the same unconformable relationships and hence were part of a regional event and not deposited in local basins. He also suggests that the Sanpoil syncline may be bounded on at least the west side by low-angle faults and that these Eocene rocks may be a synclinal allochthon rather than a graben.

Kootenay Arc

The Kootenay arc is a crescent-shaped structural belt consisting of folded and faulted rocks ranging in age from Proterozoic to middle Jurassic. It extends from north of Revelstoke in southeastern British Columbia southward along Kootenay Lake and across the International Boundary into northeastern Washington. The structural trend swings to the southwest as the Kootenay arc crosses into the United States. Here it begins to spread out before it apparently disappears beneath the basalt flows of the Columbia plateau (Figure 1). It is bounded on the west by high-grade metamorphic rocks of the Shuswap complex in Canada and their southern equivalents in Washington State. The Belt-Purcell anticlinorium lies to the east of this belt consisting of older, more openly-folded and faulted rocks.

A zone of cataclasis and shearing separates Shuswap equivalent rocks from those belonging to the Kootenay arc. Metamorphic grade changes abruptly across this zone, accompanied by a change in structural trend. Metamorphic isograds are truncated at this zone suggesting that this feature formed relatively late in the structural development of this area. Ross (1970) suggests that the Kootenay arc becomes an integral part of the Shuswap complex near Revelstoke, B.C. The lowest allochthonous nappe in this area is cored by granite gneiss which he proposes may be correlative to units farther west in the Thor-Odin and Valhalla gneiss domes.

The oldest rocks lying within the Kootenay arc region in northeastern Washington belong to the Precambrian Deer Trail Group and the Belt Supergroup. Precambrian rocks in and around the Metaline mining district were called the Priest River Group by Park and Cannon (1943) and appear to be correlative with the Deer Trail Group (Becraft and Weis, 1963; Yates, 1970; Miller and Clark, 1975). Miller and Clark tentatively correlate the Deer Trail Group with the upper part of the Belt Supergroup for those rocks found in the Chewelah area. The absence of Windermere units lying above those of the Belt distinguish the latter from rocks belonging to the Deer Trail Group. Beltian and Deer

Trail rocks and their equivalents characteristically consist of fine-grained quartzites, siltites, and argillites with subordinate amounts of limestone.

Latest Precambrian rocks belong to the Windermere Group and unconformably overlie rocks of the Deer Trail Group. The Huckleberry Formation comprises the lower portion of the Windermere consisting of a basal conglomerate and an overlying greenstone, named the Shedroof Conglomerate and Leola Volcanics, respectively, by Park and Cannon (1943) in the Metaline area. The overlying Monk Formation also contains a basal conglomerate and generally consists of slate and argillite with interbedded units of dolomite, conglomerate, and quartzite.

Precambrian sedimentary rocks in northeastern Washington most likely originated when a portion of the North American Continent began to rift away late in the Precambrian, forming an elongate basin which began to receive sediments from surrounding highlands (Stewart, 1972); Sears and Price, 1978). Precambrian Deer Trail rocks lying just west of 118° west longitude (Huntting and others, 1961) apparently mark the minimum western extent of the North American craton at the time of rifting. Continued rifting produced a stable, Atlantic-type continental margin which apparently remained as such up until the Mesozoic. Sediments were deposited on attenuated continental or oceanic crust and continued to accumulate here throughout Late Precambrian and Paleozoic time with only occasional periods of non-deposition recorded in the sedimentary pile.

Cambrian rocks found in the Kootenay arc generally consist of quartzites and phyllites with lesser amounts of limestone and dolomite.

Rocks of Ordovician, Silurian and Devonian age consist primarily of black slate with scattered occurrences of conglomerate and limestone. Stratigraphy of the upper Paleozoic is poorly known in this region but Mississippian age rocks are dominantly carbonate with minor amounts of argillite (Miller and Clark, 1975).

Several workers in the Canadian portion of the Kootenay arc identify at least two (Fyles, 1964, 1967) and in some cases three phases of deformation (Ross, 1968; Ross and Kellerhals, 1968; Crosby, 1968). Phase 1 structures comprise the dominant style throughout this fold belt. These folds are overturned, strongly asymmetrical isoclinal folds which developed an axial-plane cleavage. The axes of these folds lie parallel to the trend of the arc axis and plunge gently (<20°) north or south. These folds are developed at all scales. Crosby (1968) and other workers report that Slocan Group rocks of Triassic age are affected by phase 1 folding. Ross (1970) suggests that these folds may be modified phase 3 folds and that in fact phase 1 deformation did not affect Slocan age rocks.

Phase 2 folds are more open asymmetric structures with planar limbs and rounded hinges (Ross, 1970). They are similar in style, have variable amplitudes, and show an axial plane cleavage. Ross (1970, p. 55) describes phase 3 folds as "... more open asymmetric shear and/or flattened flexural slip structures. Their limbs are frequently planar and may have angular or sub-rounded hinges". They generally have an axial-plane cleavage that dips steeply to the east or northeast.

Several authors suggest that these structures formed through one continuous period of deformation (Crosby, 1968; Fyles, 1964; Ross, 1970). Crosby proposes that rise and lateral spreading of the infrastructure under the suprastructure crowded the rocks eastward against the Purcell anticlinorium. Ross concludes that phase 1 structures formed through easterly movement of nappes with phase 3 structures resulting from backfolding of these nappes off the rising Purcell basement. Phase 2 structures formed as a reaction between the easterly motion and the more rigid Purcell basement. Although these two workers roughly agree on the forces and movements involved, they differ significantly on the timing of these events. Crosby and most other workers assign a post-Slocan time period of deformation forming the structures in the Kootenay arc. Ross suggests that phases 1 and 2 developed before deposition of Slocan Group rocks with only phase 3 affecting them. Problems exist, however, with Ross' timing sequence as it necessitates the inclusion of a high-grade metamorphic event at the same time as deposition of those metamorphosed sediments. Metamorphism apparently reached its highest grade late in phase 1 or early phase 2 deformation. Ross further points out that structural trends differ east-west across a major sole thrust which separates easterly verging allocthonous cover from westerly verging structures in parautochthonous rocks.

Detailed, regional structural analysis has not been published for the portion of the Kootenay arc south of the International Boundary in northeastern Washington. Styles of folding here appear similar to those farther north but it is not known whether they fit into the same deformational scenario. Yates (1970) divides this part of the Kootenay arc into four tectonic units, from east to west: 1) homoclinal belt,

2) fold belt, 3) thrust belt, and 4) a Jurassic volcanic province. Precambrian and Cambrian rocks of the homoclinal belt generally strike northeast and dip to the northwest. This belt is bounded on the north by the Slate Creek fault and on the west by the Jumpoff Joe fault (Figure 3). Large isoclinal and recumbent folds have been mapped in the Chewelah area (Figure 4) along with more open structures (Miller and Clark, 1975). These folds are westward verging where they lie structurally below the major Jumpoff Joe thrust located to the west. Axes of folds lying within the fold belt trend northeasterly and generally consist of lower and middle Paleozoic rocks. Several folds mapped in the Metaline area appear as southern extensions of the Sheep Creek anticline and related folds located farther north in British Columbia. Some of these folds are also westward verging yet there does not appear to be any regional consistency in vergence. Later high-angle faulting divided the fold belt into separate structural blocks around the Metaline area.

The thrust belt trends obliquely across the trend of the earlier-formed folds of the fold belt. These faults generally trend east-west and for the most part dip varying amounts to the south. This episode of thrusting post-dates the formation of the northeasterly trends of the fold belt and related earlier thrust faults. These later thrusts appear to be part of a single system which separates two blocks north and south of the faults. Many of these thrusts found in the Northport (Yates, 1971) and Deep Creek (Yates, 1964) areas have been cut and offset by a period of high-angle faulting (tear faults of Yates, 1970, p. 34).

Several models have been proposed to explain the origin of the Kootenay arc. Crosby (1968) proposes that the arc's shape formed late when rise of the gneiss domes further crowded rocks in the middle-arc region eastward. Ross suggests that the arcuate form of the belt arose from the easterly crowding and northerly spreading of allochthonous nappes above a sole thrust against the more rigid northwesterly plunging mass of parautochthonous cover and Purcell basement. The zone of cataclasis and shearing located at the eastern edge of the Shuswap metamorphic complex may represent a gently-dipping detachment surface along which rocks of the Kootenay arc moved off the eastern part of the complex during dome formation (Read, 1977). This movement probably occurred late in the development of the Kootenay arc.

Price (1980) suggests that sediments of the Kootenay arc were deposited outboard of the boundary between the Paleozoic shale and carbonate facies, which were part of a thick sedimentary prism accumulating at the margin of the North American craton. Subsequent development of a Benioff zone during Jurassic time resulted in eastward tectonic transport and accretion of these sediments onto the edge of the continental craton. This resulted in the development inland of a zone of convergence where folding and thrusting occurred eastward in response to this compression from the west. Tectonic slides around metamorphic culminations such as the Shuswap are common but probably cannot account for overall convergence across the belt.

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