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DEPOSITIONAL FACIES, PETROGRAPHY, AND RESERVOIR POTENTIAL OF THE FORTRESS MOUNTAIN FORMATION (LOWER CRETACEOUS), CENTRAL NORTH SLOPE, ALASKA

By

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ABSTRACT

The Fortress Mountain Formation of early Albian (Early Cretaceous) age is a thick clastic wedge of largely deep-water origin that was deposited in a foredeep immediately north of the Brooks Range orogen. The formation consists of shale, sandstone and conglomerate, and appears to be made up of many overlapping submarine fan complexes, each one of limited lateral extent. Structural complications preclude lateral tracing of units across the outcrop belt. However, thick units of sandstone and conglomerate on the south, which are mostly inner fan and submarine canyon facies, apparently grade into thin-bedded, fine-grained, outer-fan and basin-plain turbidites to the north. Paleocurrent directions in the northern facies were to the east-northeast, indicating an easterly slope of the basin.

The sandstones of the Fortress Mountain Formation are subquartzose lithic sandstones, which contain much matrix or pseudomatrix, and authigenic calcite, chlorite and quartz cements. Hydrocarbon reservoir potential appears to be poor. Moreover, most of the Fortesss Mountain would probably be a thin-bedded, outer-fan or basin-plain facies in the subsurface north of the outcrop belt.

INTRODUCTION

The Fortress Mountain Formation of early Albian (Early Cretaceous) age is a thick clastic wedge of largely deep-water origin that was deposited in a foredeep immediately north of the Brooks Range orogen. The formation crops out discontinuously in a wide, structurally complex belt along the southern part of the Southern Foothills of the Brooks Range. Outcrops are restricted to the area between Elusive Lake east of the Sagavanirktok River on the east and the Kukpowruk River area on the far west, a distance of about 600 km (fig. 1). Areal geologic mapping projects in the late 1940's and early 1950's covered much of the area of Fortress Mountain outcrops. The general lithologic and stratigraphic aspects of the formation are discussed in subsequent reports, which include, from east to west, Keller, Morris, and Detterman (1961); Detterman, Bickel, and Gryc, (1963); Patton and Tailleur (1964); Chapman, Detterman, and Mangus (1964); Tailleur, Kent, and Reiser (1966), Tailleur and Kent (1951); Tailleur, Kent, and Reiser (1951); Sable, Dutro, and Morris (1951); and Chapman and Sable (1960).

This report covers primarily the central part of the Fortress Mountain outcrop belt (fig. 2). In addition to reviewing the general stratigraphy of the Fortress Mountain Formation, the purpose of this report is to discuss (1) depositional environments and facies patterns, (2) petrography and (3) the subsurface projection in relation to hydrocarbon reservoir potential. Many of the conclusions are necessarily highly interpretive and therefore, supporting evidence is discussed in more detail.

This report is based on one month of helicopter-supported field investigations by the authors between July 23 and August 21, 1980. Adverse weather conditions, including early snow falls, limited field work. Consequently, the areal coverage of the Fortress Mountain outcrop belt was curtailed. The majority of the time was spent in the area between the Chandler River on the east and the lower Nuka River on the west, a distance of 280 km (figs. 1 and 2). In addition, a reconnaissance was made of Fortress Mountain outcrops in the Kukpowruk River area west of National Petroleum Reserve in Alaska (NPRA). Because of the limited time, field work was concentrated on outcrops throughout the area that would yield the most stratigraphic information.

Structural complexities and rapid facies changes account for the discontinuous nature of the outcrops of the Fortress Mountain Formation, and make lateral tracing of beds for any distance difficult or impossible. In order to more confidently project facies trends, emphasis of the field work was on interpretation of depositional environments and measurements of paleocurrent directions. Most of the sedimentologic observations are generalized in order to grossly relate depositional facies to the paleogeography. With local variations, the conclusions arrived at in this study would probably be applicable to much of the remaining parts of the outcrop belt of the Fortress Mountain Formation.

Figure 3 diagrammatically shows our interpretations of the gross facies relations of the Fortress Mountain Formation and lower part of the Torok Formation.

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Egbert made the petrographic analyses and prepared the section on Petrography. Molenaar prepared the remaining part of the text.

TYPE SECTION AND DEFINITION

The Fortress Mountain Formation was named by Patton (1956, p. 219) from exposures on Fortress Mountain. The type section is a composite of several partial sections exposed along the Kiruktagiak River and on Castle Mountain, where a thickness of approximately 3,000 m was computed (fig. 4).

The Fortress Mountain terminology was applied to a coarse southern facies that formerly was included in the Torok Formation. The Torok is now restricted to the predominantly shaly facies to the north. The two facies are separated by either a zone of intense thrust faults or a band in which there are few exposures (Patton, 1956, p. 219); however, the Fortress Mountain Formation is undoubtedly equivalent to the lower part of the Torok Formation to the north in the Southern Foothills and southern part of the Northern Foothills.

The Fortress Mountain as defined includes all strata above the Okpikruak Formation (Lower Cretaceous, Neocomian) or older formations in the southern part of the outcrop belt where the top of the unit is not exposed. To the north it intertongues with, and is overlain by the Torok Formation (fig. 3).

CHARACTER AND THICKNESS

The Fortress Mountain Formation consists of a thick sequence of sandstone, conglomerate and shale. Outcrops are limited to discontinuous cutbank exposures and to isolated hilltops or mountain tops. Most of the outcrops are moderately to tightly folded. Large areas of tundra-type vegetation-covered colluvium flats and gentle slopes separate the outcrops, making it difficult or impossible to trace stratigraphic units laterally. In addition, the units are lenticular owing to the nature of their deposition. The isolated hills and mountains along the outcrop belt are held up by thick units of sandstone or conglomerate giving a misleading impression that coarse clastics are predominant in the formation. Shale is the dominant lithology as indicated at the type section (fig. 4). Siltstone is also common within the shale units. The shale is generally dark gray, silty and non-fissile although fissile shale has been reported (Chapman and others, 1964, p. 353). Concretion zones commonly delineate bedding within the shale. Bentonitic shale and bentonite were observed at only one outcrop; this was on the east bank of the Chandler River in section 1, T. 9 S., R. 2 W.

The sandstone is generally greenish-gray, poorly sorted, very fine to coarse-grained graywacke in the southern part of the outcrop area, and becomes finer grained to the north. The grains consist mostly of lithic fragments in a clayey chloritic matrix. In the Kukpowruk River area far to the west, the sandstones contain more quartz, and characteristically are very calcareous and micaceous. Porosity appears to be very low in all sandstones. Details of the petrography are discussed later.

The conglomerate is mostly poorly sorted, largely disorganized (lacking stratification, grading or clast orientation) and consists of pebbles, cobbles and minor boulders. The clasts include chert, mafic igneous rocks, and sandstone or quartzite in various proportions with lesser amounts of limestone and shale. Most of the chert clasts appear to be of sedimentary origin, but some are silicified volcanic rocks. The dominant clast type is not the same in all areas, which reflects differences in the rocks exposed in the adjacent source terranes, either laterally or vertically, during Fortress Mountain time. Casual observations indicate that chert is the dominant rock type in the conglomerates in the Fortress Mountain-Castle Mountain area, sandstone and mafic igneous clasts are dominant in the Ekekavik Mountain area, mafic igneous clasts are dominant in the Swayback Mountain area; and chert, mafic igneous rock, and sandstone clasts occur in aproximately equal proportion in the Kiligwa River area.

Bedding ranges from thick and massive, such as in many of the conglomerate and sandstone units prominantly exposed in the southern part of the outcrop belt, to thinly interbedded flyschoid sequences exposed along river cutbanks to the north. Thin-bedded sequences, however, do occur within the massive southern facies. The massive conglomerate and sandstone units are generally lenticular and grade laterally into thinner bedded sequences or shale along depositional strike (fig. 4). Bedding characteristics are discussed in more detail under "Depositional Environments".

The 3,000-m thickness calculated for the type section is the thickest reported section of the Fortress Mountain Formation. Other generalized sections measured by previous workers, range from about 450 m to 1,800 m, (Keller and others, 1961 p. 200; Patton and Tailleur, 1964, p. 452; Chapman and others 1964, p. 355; and Chapman and Sable, 1960, p. 72). None of these sections, including the type section, is a complete section; the top of all sections in the southern part of the outcrop belt is a Holocene erosion surface, and the base is covered, although the base of the type section is near older rocks. In the northern part of the outcrop belt, the Fortress Mountain Formation grades into the lower part of the Torok Formation (fig. 3).

CONTACT RELATIONS

Although the basal contact with older rocks is always covered, the Fortress Mountain Formation is interpreted to rest unconformably on older rocks, usually the Okpikruak Formation of Neocomian (Early Cretaceous) age. In some areas the contact is considered to be an angular unconformity (Patton and Tailleur, 1964, p. 452). This is apparently the relationship in the southern outcrop belt in the areas of Castle Mountain, Fortress Mountain, Ekakevik Mountain and Swayback Mountain. Faulting and structural complexities, however, are common in these areas and some of the relationships are subject to interpretation. In the Castle Mountain-Fortress Mountain areas, the Fortress Mountain Formation overlies a chaotic assemblage of separate blocks of either chert, limestone, mafic igneous rocks or sandstone ranging in age from Mississippian to Early Cretaceous (Neocomian) (fig. 5). These blocks which are as much as 100 m or more across, have been interpreted to be slivers in a pre-Fortress Mountain thrust zone (Patton and Tailleur, 1964, p. 452), or part of a widespread olistostrome of Neocomian age (Mull and others, 1976, p. 25). Either interpretation suggests intense tectonism, at least to the south, prior to Fortress Mountain deposition. Relationships are apparently similar at Ekakevik Mountain and Swayback Mountain, although the underlying chert and mafic igneous rocks in those areas are not as chaotic and have more continuity.

The nature of the unconformity in context with the depositional setting should be considered. Wherever the basal part of the Fortress Mountain is exposed, the basal rocks are interpreted to be deep-water deposits. (Deep water is here considered as being below the effect of storm wave base or surface currents, and in most cases is probably of at least bathyal depths.) Unconformities may be the result of submarine scouring along submarine canyons cutting into a deformed basin slope. Along Anuk Creek (section 7, T. 8 S., R. 26 W.) about 10 km northwest of Swayback Mountain, the faulted core of an anticline developed in Fortress Mountain strata contains an outcrop of fossiliferous cherty shales of the Shublik Formation (Triassic) and lapilli tuff of Jurassic(?) age. A short distance downstream, an outcrop of Fortress Mountain conglomerate contains angular clasts of chert and organic shale, presumably derived from the Shublik Formation. This conglomerate is interpreted to be a submarine channel, and some of the clasts probably were scoured from the channel walls up the basin slope to the south. Tailleur and Kent (1951, p. 24) suggested that the relationship represents deposition of the middle or upper part of the Fortress Mountain Formation on an actively growing structure within the depositional basin.

Farther north in the basin, the Fortress Mountain Formation may be conformable with older rocks, although this can not be proven at this time. In an anticlinal fold along the lower Kiligiwa River near Brady about 9 km from the mouth of the river, the Fortress Mountain lies about 100 m or less above shales and siltstones containing Valanginian fossils that are common to the Okpikruak Formation (Tailleur and Kent, 1953; and Imlay, 1961, p. 22). The character of the contact, however, is indeterminate (Tailleur and Kent, 1953, p. 7).

Seismic data in the Northern Foothills indicate that Albian or older strata progressively onlap the south-dipping Neocomian pebble shale unit (Molenaar, in preparation). Therefore, older post-Neocomian rocks may be present in the axial part of the Colville basin in the northern part of the Southern Foothills.

In the northern part of the Southern Foothills, thin-bedded turbidites of the Fortress Mountain Formation intertongue with shale of the Torok Formation. Locally, thick-bedded, coarser grained turbidites occur in this part of the area, such as near the junction of Torok Creek and the Chandler River, and near the mouth of the Etivluk River. These beds are interpreted to be more northerly extending mid-fan deposits. Previous workers included these beds in the Torok Formation (Patton and Tailleur, 1964; and Chapman and others, 1964). The placement of the contact between the Fortress Mountain and Torok Formations is arbitrary because of poor exposures and structural complications. If the contact were traceable, it undoubtedly would range in stratigraphic position.

PENECONTEMPORANEOUS DEFORMATION

Folding during Fortress Mountain time has been suggested to account for numerous local unconformities within the Fortress Mountain Formation and the overall decrease in deformation upward in the formation (Patton and Tailleur, 1964, p. 456). Some of this apparent decrease may result from competency differences between the more shaly basal portions and the massive conglomeratic portions in the upper part of the formation (Tailleur and Kent, 1951, p. 23). There are indications, however, of penecontemporaneous deformation. One indication is along the East Fork of the Etivluk River in section 25, T. 9 S., R. 17 W., where Chapman, Detterman, and Mangus (1964, p. 355) reported a local unconformity. This unconformity is interpreted here to be at the base of a deep-water conglomerate channel that truncates a thin-bedded turbidite facies with an angular difference of about 20 degrees over the outcrop width of about 150 m.

An angular unconformity has also been reported by Tailleur and Kent (1951, p. 23 - referred to as units of the Torok Formation at that time), and Tailleur and others (1966) between units of the Fortress Mountain Formation on the south side of Ekakevik Mountain. We intepreted the strata above the unconformity to be nonmarine, and thus indicating that subaerial erosion was involved. Facies relationships are discussed in more detail under "Depositional Environments".

As was reported earlier, it appears that active tectonism was taking place along the southern margin of the basin during the time of Fortress Mountain deposition. This would help to explain apparent thickness variations and some of the complex structural relations.

DEPOSITIONAL ENVIRONMENTS

The determination of depositional environments is important in analyzing the depositional history and facies patterns of the Fortress Mountain Formation, especially because structural complications and discontinuous outcrops preclude direct tracing of units within the sequence in most areas. Correct interpretation of the depositional environments and association of environments enables one to better position a rock unit paleogeographically within the basin, and hence, be able to project facies trends or patterns more accurately.

For purposes of discussion and analysis, we are subdividing depositional environments into three major categories; these are nonmarine, shallow-water marine and deep-water marine. The division between shallow water and deep water is based on the depth to which wave and surface currents are active, i.e., usually less than 50 or 100 m. Except for submarine canyon deposits, most deep-water sandstones or conglomerates were probably deposited at depths much greater than 50-100 m. Deep-water deposits are further subdivided in terms of the turbidite fan-facies model of Mutti and Ricci Lucchi (1972) with a fair degree of confidence, although there are probably significant differences between the Mutti and Ricci Lucchi model from the northern Appenines of Italy and the Fortress Mountain Formation.

It should be emphasized that the determination of depositional environments and the analog approach is highly interpretative, and may be subject to other interpretations. For this reason, some of the evidence will be discussed in more detail, especially that from the better known or previously discussed sections or areas. Also, nonmarine and shallow-water marine deposits are discussed together because they are closely related and constitute only a minor part of the Fortress Mountain Formation.

Nonmarine and Shallow Marine Deposits

Deposits interpreted to be nonmarine and shallow marine were noted in two areas along the outcrop belt between the Chandler and Nuka Rivers. These are in the upper 150 m of Castle Mountain and at least 180 m of the section on the southwest side of Ekakevik Mountain. The upper part of the Castle Mountain section is interpreted to represent a rapid upward gradation from marine shale through a poorly developed shoreface facies to a braided stream or alluvial fan sequence of conglomerate and sandstone. This interpretation is based on the following evidence: (1) A 30- to 50-m upward-coarsening transition zone, from silty marine shale below to thick-bedded conglomerate above, occurs at the base of the massive resistant conglomerates. This zone consists of interbedded and intermixed shale, sandstone and pebbly sandstone, some of which contains medium-scale crossbeds. (2) Low-angle, northerly dipping accretion planes occur in the lower part of the conglomerate and sandstone on the north side of the mountain. These may represent foreshore accretion surfaces. North-northeast-trending symmetrical ripple marks occur on one bed that was correlated across the ridge a distance of about 600 m. (3) On the southwest side of the mountain, 8+ m- thick, 18-degree, north-northeast-dipping foresets occur near the base of the massive conglomerates. These are interpreted to be Gilbert-type deltaic deposits that may have been deposited in a protected embayment or channel. (4) The non-channeling nature and the even and regular bedding of the thick-bedded conglomerate units above the transition zone are more indicative of a fluvial environment.

Inasmuch as the vertical transition from marine to nonmarine deposits is abrupt, it is probable that the lateral gradation would also be abrupt and that a shelf, if present, would be narrow. Two 6- to 12-m-thick conglomerate beds encased in shale occur about 60 m below the transitional base of the massive conglomerates on the northwest side of the mountain. The two conglomerate beds are interpreted to be submarine channels cutting into the upper slope or outer shelf.

Nonmarine deposits are also present on the southwest side of Ekakevik Mountain as reported by Hunter and Fox (1976, p. 30). In addition to the evidence reported by Hunter and Fox, we found thin coal beds a few cm thick, delicate fern leaf impressions, root casts and possible paleosols in one soft-weathered shaly and sandy interval within the conglomerates. This interval, which is at least 50 m thick, can be traced for at least 5 km along the southwest side of the mountain. About 50 to 100 m above the nonmarine zone are sandstones with low-angle cross bedding, and conglomerates, some of which contain stratified, well-sorted, well-rounded chert pebbles and granules. These deposits are interpreted to be a shallow marine or beach facies. The sandstone unit capping Ekakevik Mountain was not examined in sufficient detail, but pelecypods were collected from that unit and are listed under "Age". Hunter and Fox (1976, p. 30), who also found pelecypods in this unit, interpreted these rocks to be of shallow marine origin. Thus, the middle and upper part of Ekakevik Mountain appears to be a transgressive or "deepening upward" sequence.

Deep-Water Deposits

Most of the Fortress Mountain Formation is interpreted to be of deep-water origin. These deposits range from the thick massive conglomerates on the south, which are interpreted to be a submarine canyon facies to thinly interbedded, very fine grained sandstone and shale exposed along cutbanks as far north as the Colville River that are interpreted to be outer-fan or basin-plain deposits. These have been included in the Torok Formation on some of the available geologic maps, i.e., Chapman, Detterman and Mangus (1964).

The thick conglomerate units at Fortress Mountain, Swayback Mountain and possibly those in the lower part of the Ekakevik Mountain section are interpreted to be submarine canyon deposits at or near local entry points for coarse clastics entering the basin. On the south side of Fortress Mountain, the conglomerate unit is about 300 m thick and occurs near the base of the formation if the contact with older rocks is a deposition rather than a fault contact (fig. 5). The clasts are largely unstratified and ungraded pebbles and cobbles with minor boulders. The unit can be traced northward across a syncline for about 2 1/2 km where it grades to predominantly sandstone of probably an inner- or mid-fan facies. Tracing the unit to the east across an inferred large fault that parallels the Ayiyak River, it is intepreted to correlate with the lower part of the type section in the Kiruktagiak River-Castle Mountain areas (figs. 4 and 5).

The 50-m-thick conglomerate unit exposed on the northwest and northeast side of Ekakevik Mountain is interpreted to be either a submarine canyon or inner-fan-channel facies. The clasts range in size from pebbles to small boulders and are unstratified and ungraded, but many of the clasts are imbricated indicating a northwesterly current direction. This unit underlies the previously mentioned nonmarine section that is exposed on the southwest side of the mountain, which is an anomalous relationship. An angular unconformity, however, is indicated between these two units at one exposure on the south side of the mountain. This unconformity is shown by Tailleur and Kent (1951), and Tailleur and others (1966], and is apparent in a small area (NW/4 section 23, T. 10 S., R. 22 W.) on aerial photographs. We interpret that a fault cuts out the lower unit along Taffy Creek on the southwest side of the mountain. In other areas around the mountain, the lower unit is assumed to unconformably underlie the nonmarine unit with no apparent angular discordance.

Other conglomerate units within the outcrop belt are interpreted to be submarine channels of an inner- or mid-fan facies. These conglomerate units are commonly associated with thinly interbedded sandstone and shale intervals of interchannel deposits. These sequences are well exposed along the upper part of the Kiligwa River. Another notable exposure is along the East Fork of the Etivluk River (section 25, T. 9 S., R. 17 W.) where a channel sequence unconformably overlies a thin-bedded, outer-fan turbidite facies.

Thick sandstone units make up many of the isolated hills and mountains such as Pingaluligit Mountain, Smith Mountain and much of Liberator Ridge. Outcrops are commonly rubbly or fractured and few diagnostic features are apparent. The sandstone is generally fine to coarse grained, poorly sorted, and poorly bedded. Curved fracture planes that could be mistaken for crossbedding may be controlled by water-escapement paths. These sandstone units are interpreted to be inner- or possibly mid-fan grain-flow deposits (Facies B of Mutti and Ricci Lucchi, 1972).

Thin-bedded, more classical turbidites are common in cutbanks in the more topographically subdued areas of the northern part of the Southern Foothills. The sandstones are usually fine to very fine grained and occur as graded beds up to 2 m thick, but most are less than 20 cm thick. Partial Bouma bedding sequences (Bouma, 1963, p. 49) are easily recognized; mostly Tb-e ("a" missing) with the "c" interval, the small-scale crossbedded or ripple-bedded division, being most prevalent. Climbing ripples and contorted bedding is a common feature. Flute casts and other sole markings are abundant. Tracks and trails are also common on the base of sandstone beds. The sand/shale ratio of the more resistant outcrops in this part of the area ranges from 1:2 to 3:1. Thickening upward (lobe) sequences are thin where recognized; commonly, a cycle is only 1-2 m thick.

Most of the turbidites in the northern part of the Southern Foothills are considered to be outer-fan deposits and the more subdued outcrops are outer-fan or basin-plain deposits.

PALEOCURRENT DIRECTIONS

Paleocurrent features are numerous in the Fortress Mountain Formation, especially in the thin-bedded more distal facies in the northern part of the outcrop belt. Observations were made wherever possible and, although the number of data points is limited, a pattern does emerge (fig. 2). In the outcrops of nonmarine or shallow marine facies, current direction data are based on a limited number of medium-scale crossbeds, which show a wide scatter of directions, and parallel ripple marks. Clasts imbrication is common in some of the submarine channel or channel conglomerates. In most of these, the long axis of the clasts is parallel to the current direction. Interbedded sandstones and shales, some of which are interpreted to be inter-channel deposits, contain minor groove or flute casts on the base of the sandstone beds. Some of the current directions are anomalous, which would be expected in inter-channel deposits. By far the most numerous and consistent direction features occur in the more distal facies to the north. These consist of groove and flute casts and also small-scale ripple bedding and climbing ripples. Current directions in that part of the area are predominantly to the east-northeast.

SUMMARY OF DEPOSITIONAL PATTERNS

The Fortress Mountain Formation appears to have been rapidly deposited into an asymmetric steep-sided basin from many point sources along the ancestral Brooks Range (fig. 3). This is indicated by changes in conglomerate clast composition in different areas and by abrupt lateral facies changes along the depositional strike. An example of this is the inferred relationship between the section at Fortress Mountain (T. 10 S., R. 5 W.) and at Castle Mountain, two conglomerate-capped mountains about 16 km apart along an east-west line (figs. 4 and 5). The 300-m-thick conglomerate unit on the south side of Fortress Mountain, which is interpreted to be a submarine canyon facies, grades into a predominantly sandstone unit 2 1/2 km north across a syncline. To the east, this unit thins and apparently grades into a predominantly shale section in the lower part of the 3,000-m-thick type section of the Fortress Mountain Formation near Castle Mountain. These relationships and the many apparently discontinuous thick lenses of coarse clastics, support the interpretation that the Fortress Mountain Formation is composed of a number of, in part, overlapping submarine fan complexes, each one of limited lateral extent.

Rapid downdip facies changes into the basin are also apparent, even though direct correlations are usually not possible because the area has been telescoped into complex folds and faults. However, turbidites of the Fortress Mountain Formation are finer grained and more thinly bedded to the north. The thick conglomerate sections are always on the south side of the outcrop belt. The rapid change from conglomerate to sandstone noted at Fortress Mountain is also exemplified by the almost continuous exposures along the Kiligwa River which transects about 27 km of the outcrop belt (Tps. 5-8 S., R. 2 W.). Although the strata are tightly folded and faulted, and stratigraphic correlation across the belt can not be established, there is a marked gradation of proximal to distal facies from south to north. In the southern part of the outcrop belt, there are many conglomerate units that are interpreted to represent inner-fan channel deposits. About 16-20 km to the north, the Fortress Mountain Formation consists of thin-bedded, fine-grained turbidites of an outer-fan or basin-plain facies. This section includes the basal part of the Fortress Mountain Formation inasmuch as nearby pre-Fortress Mountain Valanginian (Early Cretaceous) fossils were found in shales in the exposed core of the anticline in section 36 T. 5 S., R. 28 W. near Brady about 9 km from the mouth of the river (Tailleur and Kent, 1953, p. 12).

Deformation during Fortress Mountain deposition is indicated by unconformities within the formation and apparent thickness variations of the unit along the southern part of the basin.

Paleocurrent directions from the outer-fan or basin-plain facies associations indicate a current flow to the east-northeast (fig. 2). Although the sediments were probably derived from the south, the turbid flow directions were influenced by an easterly slope of the depositional basin. In the Northern Foothills, seismic data indicate a gentle south-dipping basin slope during the time of deposition of the lower Torok Formation and (or) Fortress Mountain Formation (Molenaar, in preparation). Thus it appears that the northern part of the Southern Foothills area may coincide with the depositional axis of the Colville basin during at least part of Fortress Mountain time (fig. 3).

AGE

Megafossils are rare in the Fortress Mountain Formation and only two collections of pelecypods were made during this study. Patton and Tailleur (1964, p. 456), and Chapman, Detterman, and Mangus (1964, p. 357) list and discuss previously collected megafossils and microfossils, many of which are long ranging or nondiagnostic. The diagnostic species include the ammonites *Colvillia crassicostata* Imlay, C. *Kenti* Imlay, *Beudanticeras (Grantziceras)* aff. (Whiteaves), and the pelecypods *Aucellina dowlingi* McLearn, *Thracia kissoumi* McLearn, *Pleuromya kelleri* Imlay, *Placunopsis nuka* Imlay, and *Inoceramus* cf. I. altifluminus McLearn. On the basis of the occurrence of *Colvillia crassicostata* Imlay and *Aucellina dowlingi* McLearn, Imlay (1961, p. 8) has assigned a probable early Albian (Early Cretaceous) age to the

Fortress Mountain Formation. These fossil collections were considered to be from the lower 1,000 m of the Fortress Mountain. *Colvillia crassicostata* was also collected from a turbidite zone in what is mapped as Torok Formation along the Chandler River about 1,250 m below the top of the Torok at its type section. (Patton and Tailleur, 1964, p. 461). This turbidite zone is the stratigraphically highest significant turbidite deposit in the type section although there are large covered parts of the section in which the lithology is obscured. On the basis of this fossil and *Beudanticeras* collected elsewhere in this part of the Torok Formation, Imlay (1961, p. 4) correlates the lower part of the Torok with the lower part of the Fortress Mountain Formation. We are suggesting that the lower part of the Torok type section is relatively high in the total Torok-Fortress Mountain interval. Seismic data indicate that this interval may be as thick as 6,000 m in the southern part of the Northern Foothills (Molenaar, in preparation).

From the faunal evidence, it appears that the time represented by Fortress Mountain deposition was relatively short in spite of the great thickness of the unit. Although there is no faunal evidence, it is possible that the lower part of the Fortress Mountain-Torok interval could range down into the Aptian in the axial part of the deep Colville basin.

The two fossil collections made during this study were identified by D. L. Jones and J. W. Miller of the U.S. Geological Survey and are listed as follows:

80AMK-176, USGS locality M7413, from north bank of Colville River, NW/4 sec. 31, T. 6 S., R. 19 W., lat 68° 53′03" N., long 156° 31′03" W.
Inoceramus cf. *I. altifluminis* McLearn. Early Cretaceous (early-middle Albian).

80AMK-189, USGS locality M7414 from high on southwest side of Ekakevik Mountain, SE/4 sec. 8, T. 10 S., R. 22 E., lat 68° 35′11" N., long 157° 04′57" W.

Panope elongatissima McLearn
Tancredia stelcki McLearn
Thracia stelcki McLearn
Yoldia kissoumi McLearn
Astarte sp.

This assemblage is considered Early Cretaceous (Albian) in age.

HYDROCARBON OCCURRENCES AND ORGANIC GEOCHEMISTRY

Solid hydrocarbon dikes or fracture fillings up to 25 cm wide were observed at several localities in the Fortress Mountain Formation, and in one place, in the underlying Okpikruak Formation. Patton and Tailleur (1964, p. 496) also reported similar occurrences of asphaltic matter in the Okpikruak, Fortress Mountain and Torok Formations. The solid hydrocarbon is black, brittle, and shiny, similar to coal except for being more brittle and breaking into smaller fragments (granule to small pebble size) than coal.

Most occurrences of the solid hydrocarbon are within shale sections, but some cut across sandstone beds. In no case was oil staining observed in the adjacent sandstones. At one locality, the hydrocarbon was found along a fracture in a sandstone bed in which the fracture was lined with quartz crystals. This clearly indicates that the hydrocarbons came in after lithification and induration. The source of the hydrocarbons was probably either the laterally adjacent or underlying shale, or organic-rich shales of the underlying Triassic or Jurassic(?) formations.

In addition to the solid hydrocarbons, a fetid, gaseous odor was noted on freshly broken surfaces of Fortress Mountain sandstone beds in the lower Nuka River area of T. 6 S., R. 31 W. These sandstone beds are very fine grained and are of an outer-fan facies.

Organic geochemical data from 22 outcrop samples indicate that shales of the Fortress Mountain Formation are fair source rocks for petroleum. Total organic carbon ranges from 0.45 to 1.40 percent and averages about 0.80 percent. The visual kerogen is dominantly herbaceous and amorphous. Average vitrinite reflectance values range from 0.45 to 1.10; the highest values is from a single sample from the Kukpowruk River area on the far west. The average of all values is 0.65, which is within the mature range of hydrocarbon generation. Table 1 shows the organic geochemical data.

RESERVOIR DATA

Sandstones of the Fortress Mountain Formation contain abundant lithic grains and appear to have very poor reservoir potential as indicated by visual and petrographic examination of outcrop samples. The pore space is largely clay filled owing to alteration of unstable lithic fragments or to the formation of authigenic cements. Because of surface weathering and alterations, the porosity and permeability of surface samples may not be directly applicable to similar sandstones in the subsurface. However, 15 surface samples were measured for porosity and permeability by Core Laboratories, Inc. of Denver, Colorado; the results are listed in Table 2.

SUBSURFACE EXTRAPOLATION

It is clear that the Fortress Mountain Formation intertongues with the lower part of the Torok Formation. It has also been shown that bottomset or basinal beds of the Torok Formation in the coastal plain area of NPRA, which contain thin turbidites are coeval with the deltaic Nanushuk Group (Molenaar, in press). In the Northern Foothills, where the structure is complex and the quality of seismic data is not good enough to decipher stratigraphic details, it is difficult or impossible to distinguish between turbidites that may be equivalent to the Nanushuk Group and those equivalent to the Fortress Mountain Formation. Indeed, at some stratigraphic interval, turbidites equivalent to the two units may merge or intertongue. For this reason, we recommend that the Fortress Mountain Formation terminology be limited to the Southern Foothills, i.e., the outcrop belt, and that equivalent sandstone beds in the Northern Foothills be called informally lower Torok sandstones. This terminology has been used in the subsurface in the coastal plain area to the north.

Inasmuch as the sandstone of the Fortress Mountain Formation becomes finer grained and thinner bedded to the north in the outcrop belt of the Southern Foothills, very little sandstone or a more distal facies would be expected in the subsurface farther north. However, coarser clastics were contributed from many point sources, and some individual fans could extend into the Northern Foothills area. How far north these sandstone units or the entire Fortress Mountain equivalents could be expected should be considered. Seismic data in the Northern Foothills indicate that Fortress Mountain-equivalent strata or the lower part of the Torok Formation onlaps south-dipping Neocomian strata (Molenaar, in preparation). Coeval strata of the Fortress Mountain Formation probably are not present or form a condensed section north of the Northern Foothills. Thus the southern part of the Northern Foothills would be the most likely area for the subsurface occurrence of thicker or coarser grained sandstone facies. On the basis of observed direction features in the outcrop belt, the Fortress Mountain-equivalent strata in the subsurface would probably have been deposited by east-northeasterly flowing turbidity currents.

Seven wells in the Northern Foothills may have penetrated at least part of the strata equivalent to the Fortress Mountain Formation (fig. 1). Gas shows have been reported from some of these tests, but for the most part, available data indicate that the sandstone units are thin and have limited reservoir potential. This is corroborated by the outcrop and petrographic studies. However, thicker sandstone beds in combination with fracture porosity and permeability could conceivably provide a commercial hydrocarbon reservoir.

PETROGRAPHY

Thirty-nine sandstone samples from random outcrops of the Fortress Mountain Formation were examined to determine general petrographic characteristics, provenance, and factors that might affect reservoir potential. Thirty-six samples were obtained between Castle Mountain and Nuka River (fig. 2) and will be referred to as the eastern samples. Three samples of the Fortress Mountain Formation from the Kukpowruk River area on the far west (fig. 1), were also examined petrographically and will be referred to as the western samples. The petrographic analysis indicates that sandstones from the Fortress Mountain Formation are all subquartzose (<75% quartz) lithic sandstones following the classification of Dickinson (1970) modified from Cook (1960). The lithic fragment and conglomerate clast lithologies indicate that the upper allochonous thrust sequences of the central and western Brooks Range was the predominant sediment source for the Fortess Mountain Formation. The Kukpowruk River area samples, however, show significant differences from other Fortress Mountain Formation samples and suggest a different source terrane.

Most of the initial porosity of the sandstones studied has been occluded by compaction deformation of unstable lithic fragments and by the formation of authigenic calcite, chlorite, and quartz cements. These characteristics greatly reduce the reservoir potential of Fortress Mountain Formation sandstones, especially if the same characteristics occur in the subsurface.

Methods

Thin sections cut from the sandstone samples were impregnated with blue epoxy to enhance definition of pores, and stained with Alizarin Red S and sodium cobaltinitrate to facilitate identification of calcite and K-feldspar, respectively. The petrographic analysis followed the methods of Dickinson (1970) and results are summarized in tables 3 and 4, and figures 6 through 9, following the methods of Dickinson and Suczek (1979). A minimum of 300 points per thin section were counted to determine framework modes (quartz (Q), feldspar (F), and lithic fragments (L)), cements and visible porosity.

Volumetric percentages of 24 sandstone grain variables were determined and combined into the 16 catagories shown on table. 3. Normalized volumetric percentages of the following groups of framework grains are presented in table 4 and displayed in figures 6 through 9 in order to characterize Fortress Mountain Formation sandstones. The Q_tFL data in figure 6 are normalized percentages of total quartzose grains (Q_t), total feldspar (F), and unstable lithic fragments (L). The Q_mFL_t data in figure 7 are normalized percentages of monocrystalline quartz (Q_m), total feldspar (F), and total lithic fragments (L_t), which includes unstable lithic fragments, chert, quartzite, and polycrystalline quartz fragments. The $Q_pL_vL_s$ data in figure 8 are normalized percentages of polycrystalline quartz (Q_p), which includes polycrystalline quartz, chert, and quartzite fragments, volcanic lithic fragments (L_v), and unstable sedimentary lithic fragments (L_s). The Q_mPK data in figure 9 represents normalized percentages of monocrystalline quartz (Q_m), plagioclase (P), and K-feldspar(K).

The Q_tFL and Q_mFL_t data both include total framework grain populations: the Q_tFL data, where all quartzose grains are grouped together, emphasize grain stability, and the Q_mFL_t data, where all lithic fragments, including chert, polycrystalline quartz, and quartzite fragments, are grouped together, emphasize the grain size of the source rocks. The $Q_pL_vL_s$ and Q_mPK data include only partial grain populations, but reveal the character of the polycrystalline and monocrystalline components of the framework, respectively.

Quartz

All of the sandstones studied are subquartzose (<75% quartzose fragments), although the finer grained samples are relatively enriched in quartz, apparently due to mechanical disaggregation of lithic fragments during transport and deposition (table 3 and figs. 6 and 7). The eastern Fortress Mountain Formation samples average 32 percent quartzose fragments, whereas the three western samples average 51 percent quartzose fragments (table 4). Polycrystalline quartz to total quartz ratios (C/Q, table 4) indicate that polycrystalline quartz (mostly chert) dominates the quartzose grain population in the eastern samples, with monocrystalline quartz dominating the quartzose grain population in the western samples. Polycrystalline quartz, of a stretched metamorphic variety, is present in minor amounts in samples from both areas, but is slightly more abundant in the western samples (table 3). Quartzite fragments are present in minor amounts in the eastern Fortress Mountain Formation samples, but were not noted in any of the three western samples.

Feldspar

Feldspar comprises a small but consistent percentage of the sandstones, averaging 9 percent of the framework grains in the eastern samples and 6 percent in the western samples. High ratios of plagioclase to total feldspar (P/F) in both areas indicate that nearly all of the feldspar present is plagioclase (table 3 and 4, fig. 9).

Lithic Fragments

Lithic fragments are the most abundant framework grains in Fortress Mountain Formation samples. The stable lithic grains (chert, polycrystalline quartz, and quartzite) have already been discussed. Unstable lithic fragments in order of decreasing abundance include, argillaceous and carbonaceous types, and mafic volcanic, limestone, metamorphic, and siltstone fragments. Argillaceous and carbonaceous lithic fragments (treated together because of their close association in many grains and difficulty of differentiation) are the most abundant unstable lithic-grain types in most samples studied. In the western samples however, limestone (calcite) clasts are most abundant followed by argillaceous-carbonaceous grains, metamorphic, and volcanic rock fragments (table 3). In the eastern Fortress Mountain Formation samples, argillaceous-carbonaceous fragments and volcanic rock fragments predominate with only minor amounts of limestone, metamorphic, and siltstone fragments.

Volcanic lithic to total unstable lithic fragment ratios are low for the western samples (average 0.18), but reach moderate amounts in the eastern samples (average 0.35) (table 4). In the eastern samples, argillaceous-carbonaceous, volcanic, and chert fragments together average 68 percent of the framework grains, whereas in the western samples the same three grain types average only 23 percent of the framework.

Accessory Minerals

Accessory minerals are present in low percentages in the samples studied, averaging 2 percent in the eastern samples and 4 percent in the western samples from the Kukpowruk River area. Muscovite accounts for almost all of the accessory mineral population in these samples, whereas in the eastern samples, accessory minerals in varying proportions include magnetite, pyrite, muscovite, pyroxene, olivine, biotite, epidote, and trace amounts of garnet. A more exhaustive discussion of heavy minerals from the Fortress Mountain Formation is found in Patton and Tailleur (1964).

Matrix

Fortress Mountain Formation sandstones are all "matrix rich." Most of the matrix however, is a pseudomatrix formed from the compaction and plastic deformation of abundant unstable lithic fragments. The initial porosity of the sandstones is almost totally occluded by the pseudomatrix, and most of the remaining pore space is filled by authigenic cements. These cements include phyllosilicates, mostly chlorite, that occur as rims on detrital grains and as radial pore fillings; calcite, occurring mainly as sparry aggregates and also replacing some framework grains; and quartz, as overgrowths on detrital quartz grains and as microgranular aggregates in pores.

Chlorite and calcite cements are present in most samples studied. In the eastern samples, chlorite and calcite cements dominate, and occur in various proportions, Quartz cement is present in minor amounts, but is most prevalent in samples from the coarser facies of the formation, especially at Castle Mountain, Fortress Mountain, and Ekakevik Mountain. In the western samples, calcite is the dominant cement.

Provenance

The petrographic analysis of Fortress Mountain Formation samples indicates different source terranes for sediment deposited in the Kukpowruk River area on the west and sediment deposited in the area between Nuka River and Castle Mountain. Conclusions based on the western samples from the Kukpowrk River area are considered tentative as only three samples were studied. However, the three samples are all similar in composition and dissimilar to the eastern samples of the Fortress Mountain Formation. In the western samples, monocrystalline quartz is the most abundant constituent followed by limestone clasts, chert, polycrystalline quartz, and argillaceous carbonaceous fragments, with only minor amounts of volcanic and metamorphic fragments and palgioclase (table 4). These framework grain lithologies are similar to the compositional data given by Bartsch-Winkler (1979) for the overlying Nanushuk Group in the same area. Both data sets indicate a similar source terrane, the Tigara uplift in the area of the Lisburne Hills and offshore, possibly including the Herald arch where a western extension of the Brooks Range schist belt may have been exposed during the Albian (Mull, in press).

The majority of samples studied are from the area between Nuka River and Castle Mountain. The samples are all compositionally similar except that fine-grained samples tend to have a higher percentage of monocrystalline quartz (table 3 and 4, figs, 6 and 7). Argillaceous-carbonaceous fragments are the most abundant constituents in these samples followed closely by volcanic rock fragments and chert. These three components make up approximately 68 percent of the framework grains and indicate a sedimentary and volcanic source terrane. This petrographic analysis of Fortress Mountain Formation sandstones supports the contention of Mull (1979) and Roeder and Mull (1978) that the mafic igneous and gabbroic pebbles in the Fortress Mountain conglomerates indicate a source terrane composed of the Misheguk sequence (uppermost Brooks Range allochthon). However, the abundant fine-grained sedimentary rock fragments indicate that the underlying allochthonous thrust sequences also were dissected and supplying sediment to the basin during deposition of the Fortress Mountain Formation.

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Table 1.--Organic geochemical data for outcrop samples of Fortress Mountain Formation, North Slope, Alaska. TAI, thermal alteration index; min Ro, minimum reflectance; max Ro, maximum reflectance; mean Ro, mean reflectance; TOC, total organic carbon; A, amorphous; H, herbaceous; hu, humic; I, inert. Analytical work by Geochem Research, Inc., Houston, Texas.

Field No.	Location Sec.	Location T.	Location R.	TAI	Vitrinite Reflectance Min. %Ro	Vitrinite Reflectance Max. %Ro	Vitrinite Reflectance Mean %Ro	TOC	Visual Kerogen (%) A	Visual Kerogen (%) H	Visual Kerogen (%) Hu	Visual Kerogen (%) I
80 AMK-101A	1	9S	2W	2.1	0.47	0.73	0.58	1.39	31	3B	23	8
80 AMK-111	15	10S	3W	2.1	.50	.76	.65	.58	25	42	17	17
80 AMK-116	34	9S	5W	2.5	.49	.77	.63	.49	0	40	40	20
80 AMK-122A	14	10S	5W	2.5	.57	.84	.71	.68	23	38	23	15
80 AMK-122B	14	10S	5W	2.5	.60	.88	.74	.70	15	38	23	24
80 AMK-122C	14	10S	5W	2.7	.62	.89	.75	.75	23	38	23	15
80 AMK-122D	14	10S	5W	2.7	.54	.87	.73	.64	9	45	27	18
80 AMK-138A	25	10S	22W	2.5	.36	.56	.45	.62	8	46	23	23
80 AMK-138B	25	10S	22W	2.3	.35	.55	.45	.45	20	50	20	10
80 AMK-138C	25	10S	22W	2.1	.37	.61	.49	.58	18	45	27	9

80 AMK-147A	7	10S	22W	2.1	.41	.64	.53	.74	23	38	23	15
80 AMK-147B	7	10S	22W	2.3	.43	.63	.56	.75	15	38	23	23
80 AMK-152	1	9S	19W	2.4	.42	.65	.54	.76	0	50	20	30
80 AMK-157B	18	6S	17W	2.3	.46	.69	.57	1.26	0	42	33	25
80 AMK-159C	25	9S	17W	2.1	.60	.84	.73	.74	0	40	30	30
80 AMK-159D	25	9S	17W	2.1	.46	.71	.58	.75	0	36	36	27
80 AMK-167B	13	8S	28W	2.1	.54	.76	.64	.94	8	42	33	17
80 AMK-167C	13	8S	28W	2.1	.51	.70	.61	.84	0	50	30	20
80 AMK-167D	13	8S	28W	2.1	.51	.70	.61	.84	0	50	30	20
80 AMK-167E	13	8S	28W	2.3	.52	.67	.60	.83	31	38	15	15
80 AMK-182B	13	6S	31W	2.4	.87	1.08	/99	1.40	0	38	31	31
80 AMK-192B	35	10S	50W	2.7	.93	1.25	1.10	.74	0	40	30	30

Table 2.--Porosity and permeability values* from selected outcrop samples of Fortress Mountain Formation

Sample No.	Location Section	T.	R.	Porosity %	Permeability millidarcys	Facies**
80 AMK-101B	C 1	9S	2W	10.0	0.11	Facies C, mid to outer fan
80 AMK-104A	SW/4 15	10S	3W	6.5	<0.01	Shallow marine - nonmarine?
80 AMK-118A	NE/4 35	9S	7W	5.8	0.07	Facies C, mid fan
80 AMK-124	E/2 12	10S	5W	8.8	<0.01	Facies B, inner fan
80 AMK-156	NW/4 19	6S	17W	6.4	0.03	Facies D, outer fan
80 AMK-160A	NW/4 3	9S	14W	8.5	<0.01	Facies D, outer fan
80 AMK-166A	C W/2 2	8S	28W	6.3	0.02	Facies E, inner or mid fan
80 AMK-172	NW/4 29	5S	27W	11.9	0.04	Facies C or D, outer fan
80 AMK-176	NW/4 31	6S	19W	9.7	0.02	Facies D, outer fan
80 AMK-180	N/2 22	5S	25W	14.1	0.46	Probably Nanushuk-equiv. turbidites
80 AMK-184	E/2 20	5S	29W	3.0	<0.01	Facies D, outer fan
80 AMK-189	SE/4 8	10S	22W	7.4	0.05	Shallow marine?
80 AMK-190	NW/4 1	9S	46W	4.1	0.11	Facies B, mid fan
80 AMK-192	E/2 35	10S	50W	2.2	0.10	Facies B, mid fan
80 AMK-196	SW/4 34	8S	9W	8.1	<0.01	Facies B, mid fan

*Procedure used is from American Petroleum Institute (1960). Calculated permeabilities are air permeabilities and have not been corrected for the Klinkenberg effect.

**Facies B, C, D etc., are interpretations based on the submarine fan model of Mutti and Ricci Lucchi, 1972.

Table 3. Percentages of total constituents and grain size of Fortress Mountain Formation sandstone samples.

	Sample No. 80AMK-	Location Sec.	T.	R.	Q_m	Q_p	C_q	Q_{zt}	P	K	Slt	Ac	Lms	V	M	Accm	Cal	Q	Cl	Por	Grain Size
	101B	1	9S	2W	5	5	13	2	5	0	3	46	2	2	0	0	7	0	7	3	C
	101C	1	9S	2W	5	1	32	2	5	0	1	25	2	4	1	1	17	0	2	1	C
	104A	15	10S	3W	0	0	32	1	2	1	2	29	1	18	1	1	1	8	2	1	C
	113	20	10S	3W	2	Tr	26	1	3	0	1	16	0	39	0	0	0	1	11	0	C
	118A	35	9S	7W	10	1	19	0	11	0	0	17	5	15	0	Tr	15	0	7	0	M
	124	12	10S	5W	8	2	21	2	7	3	1	30	0	20	Tr	1	0	4	0	1	M
	125	9	10S	4W	3	1	14	1	8	0	1	22	2	38	0	0	2	1	6	1	C
	136	5	10S	22W	3	2	14	4	3	0	2	41	Tr	21	2	Tr	3	1	3	0	C
	137D	16	10S	22W	12	4	10	17	2	0	10	32	1	7	1	1	1	Tr	2	0	C
	152	1	9S	19W	5	1	8	3	8	0	2	32	2	27	Tr	2	3	0	6	0	M
	153B	1	9S	20W	7	2	12	6	4	0	2	31	3	20	1	1	2	1	8	0	M
	154	30	8S	19W	6	1	16	3	9	0	6	30	2	10	1	0	10	Tr	6	0	C
	156	19	6S	17W	26	2	9	Tr	11	3	1	16	3	3	2	1	15	1	5	1	F
	157A	18	6S	17W	10	2	14	2	6	0	2	21	2	13	2	1	4	Tr	19	1	C
	158	24	7S	18W	19	4	7	1	7	Tr	1	11	3	9	3	3	7	0	23	1	F
Eastern Samples	159A	25	9S	17W	8	3	4	3	6	1	3	29	Tr	22	1	2	8	Tr	10	0	M
	159B	25	9S	17W	4	1	10	2	4	4	1	27	5	21	0	0	12	.0	8	1	C
	160A	3	9S	14W	3	Tr	15	1	9	Tr	1	21	1	34	0	4	1	0	10	0	C
	161	35	9S	14W	3	1	17	4	4	2	1	23	0	36	0	0	5	0	4	0	C
	166A	2	8S	28W	10	5	5	2	9	4	1	19	1	19	2	5	2	0	14	2	M
	167A	13	8S	28W	3	4	12	7	7	Tr	4	22	2	29	Tr	2	2	0	6	Tr	C
	169	35	6S	28W	4	1	7	2	9	0	1	15	1	27	1	Tr	28	0	3	1	M
	172	29	5S	27W	20	2	1	0	6	0	0	7	39	5	2	2	0	0	9	7	F
	173	25	7S	29W	3	6	9	2	8	3	2	30	0	28	1	2	0	0	6	Tr	C
	175	30	10S	16W	8	1	4	2	9	Tr	2	26	3	21	Tr	3	0	0	20	Tr	M
	176	31	6S	19W	25	4	11	0	7	0	1	20	1	3	2	1	1	0	18	6	F
	177	7	7S	25W	4	2	19	2	4	0	2	29	1	23	1	Tr	8	0	4	1	C
	181	3	7S	20W	12	3	9	1	9	1	Tr	15	7	9	2	1	28	0	3	0	M
	182	13	6S	31W	27	3	10	0	8	0	1	12	14	3	0	2	9	0	8	3	F
	184	20	5S	29W	29	1	4	0	6	0	1	9	16	2	3	4	20	0	4	1	F
	186	8	10S	22W	4	1	6	0	3	2	3	41	1	10	1	Tr	22	2	4	0	M
	187B	8	10S	22W	9	4	12	0	7	2	3	24	0	15	1	1	0	4	15	3	M
	189	8	10S	22W	12	2	8	0	9	0	3	23	0	11	2	7	1	2	19	1	F
	193	14	9S	10W	4	1	22	0	3	0	3	23	0	32	Tr	2	8	0	0	2	C
	196	34	8S	9W	4	2	12	1	5	0	2	14	1	43	0	1	7	0	8	Tr	C
	197	23	9S	7W	8	2	13	Tr	8	1	1	21	0	28	1	2	0	2	6	6	C
Average					9	2	13	2	6	1	2	23	3	19	1	2	7	1	8	1	
Western Samples	190	1	9S	46W	24	4	4	0	1	0	Tr	6	33	3	2	6	12	0	5	0	F
	191B	18	10S	45W	18	7	11	0	8	0	0	8	11	5	6	3	16	0	7	0	M
	192A	35	10S	50W	20	11	7	0	3	2	1	4	11	5	6	2	28	0	0	0	M
Average					21	7	7	0	4	1	Tr	6	18	4	5	4	19	0	4	0	

EXPLANATION FOR TABLE 3

Ac -- Argillaceous-carbonaceous fragments, includes all gradations from claystone to shale to fragments of organic debris.

Accm -- Accessory minerals, in order of decreasing abundance include magnetite, pyrite, muscovite, pyroxene, olivine, biotite, and garnet.

Cal -- Calcite cement, usually sparry, often replacing framework grains.

Cl -- Phyllosilicate cement, mostly chlorite, occurring as linings on framework grains and also as radial pore fillings.

Cq -- Chert, includes dense, nearly isotropic varieties to well crystallized aggregates. Some contain euhedral calcite rhombs (probably from silicified limestones); others contain no inclusions.

K -- K-feldspar, probably orthoclase.

Lms -- Limestone fragments, includes many varieties ranging from rounded calcite clasts (probably from recyrstallized limestone) to bioclastic, microgranular and micritic types.

M -- Metamorphic rock fragments, mostly quartz-mica tectonites.

P -- Plagioclase, highly altered, usually showing albite twinning.

Por -- Pore space.

Q -- Quartz cement, occurring as overgrowths on quartz grains and as microgranular pore fillings.

Q_m -- Monocrystalline quartz

Q_p -- Polycrystalline quartz, mostly displaying stretched and sutured internal grain contacts, probably of metamorphic origin.

Q_{zt} -- Quartzite, composed mostly of monocrystalline quartz, chert, and mica. The quartzite fragments are probably derived from the Kanayut Group.

Slt -- Siltstone fragments.

Tr -- Trace amounts.

V -- Volcanic rock fragments, mostly mafic varieties with laths of feldspar in parallel or subparallel alignment set in a chlorite or isotropic to nearly isotropic groundmass. Also includes minor amounts of mafic hypabyssal grains.

Table 4. Mean framework modes of Fortress Mountain Formation sandstones.

	Sample No. 80AMK-	Location Sec.	T.	R.	Q_t	F	L	Q_m	F	L_t	Q_p	L_v	L_s	Q_m	P	K	C/Q	P/F	V/L
	101B	1	9S	2W	29	6	65	6	6	88	26	4	70	53	47	0	0.78	1.0	0.03
	101C	1	9S	2W	52	7	41	7	7	86	53	7	40	50	50	0	.87	1.0	.13
	104A	15	10S	3W	39	3	58	0	3	97	40	23	37	13	63	24	.99	.71	.32
	113	20	10S	3W	32	3	65	2	3	95	32	47	21	36	64	0	.95	1.0	.69
	118A	35	9S	7W	38	15	47	12	15	73	35	26	39	46	50	4	.68	.92	.36
	124	12	10S	5W	35	11	54	9	11	80	33	26	41	45	37	18	.75	.68	.36
	125	9	10S	4W	21	9	70	4	9	87	20	48	32	28	72	0	.83	1.0	.58
	136	5	10S	22W	24	3	73	3	3	94	23	27	50	53	47	0	.87	1.0	.32
	137D	16	10S	22W	45	2	53	13	2	85	38	9	53	84	16	0	.71	1.0	.13
	152	1	9S	19W	19	9	72	5	9	86	16	36	48	36	64	0	.73	1.0	.43
	153B	1	9S	20W	30	4	66	8	4	88	26	26	48	66	34	0	.75	1.0	.35
	154	30	8S	19W	31	11	58	7	11	82	29	16	55	39	59	2	.78	.96	.20
	156	19	6S	17W	49	18	33	34	18	48	31	15	54	66	27	7	.31	.80	.13
	157A	18	6S	17W	38	8	54	13	8	79	32	25	43	63	37	0	.66	1.0	.30
	158	24	7S	18W	47	11	42	28	11	60	31	31	38	72	27	1	.39	.96	.34
Eastern Samples	159A	25	9S	17W	23	9	68	10	9	81	16	35	50	53	43	4	.56	.91	.40
	159B	25	9S	17W	23	9	68	6	9	85	21	31	48	37	33	30	.76	.52	.40
	160A	3	9S	14W	22	11	67	4	11	85	21	47	32	26	72	2	.83	.97	.57
	161	35	9S	14W	28	7	65	4	7	90	27	44	29	34	41	25	.87	.62	.59
	166A	2	8S	28W	28	18	54	13	18	69	21	40	39	43	39	18	.51	.69	.47
	167A	13	8S	28W	28	8	64	4	8	88	28	37	35	32	66	2	.87	.96	.51
	169	35	6S	28W	20	14	66	5	14	81	19	49	32	28	72	0	.74	1.0	.60
	172	29	5S	27W	28	8	64	24	8	68	6	10	84	76	24	0	.14	1.0	.07
	173	25	7S	29W	22	13	65	3	13	84	22	35	43	21	56	23	.85	.71	.43
	175	30	10S	16W	18	12	70	11	12	77	10	34	56	48	51	1	.43	.97	.36
	176	31	6S	19W	54	9	37	34	9	57	35	12	53	79	21	0	.37	1.0	.11
	177	7	7S	25W	31	4	65	4	4	92	29	31	40	50	50	0	.87	1.0	.41
	181	3	7S	20W	37	14	49	17	14	69	28	25	47	56	41	3	.52	.92	.28
	182	13	6S	31W	52	10	38	35	10	55	31	7	62	78	22	0	.32	1.0	.11
	184	20	5S	29W	48	9	43	41	9	50	13	14	73	82	18	0	.14	1.0	.08
	186	8	10S	22W	15	7	78	6	7	87	10	18	72	48	34	18	.59	.67	.18
	187B	8	10S	22W	32	12	56	12	12	76	27	28	45	50	37	13	.64	.74	.35
	189	8	10S	22W	31	13	56	17	13	70	20	25	55	56	44	0	.46	1.0	.28
	193	14	9S	10W	31	3	66	4	3	93	29	40	31	59	41	0	.86	1.0	.54
	196	34	8S	9W	22	6	72	4	6	90	20	57	23	42	58	0	.80	1.0	.70
	197	23	9S	7W	27	12	61	10	12	78	22	44	34	45	47	8	.65	.86	.55
Average					32	9	59	12	9	79	26	28	46	50	44	6	.66	.90	.35
Western Samples	190	1	9S	46W	41	1	58	31	1	68	14	10	76	97	3	0	.23	1.0	.07
	191B	18	10S	45W	49	10	41	25	10	65	37	23	40	71	29	0	.49	.0	.16
	192A	35	10S	50W	54	7	39	29	7	64	40	26	34	80	12	8	.47	.61	.32
Average					51	6	43	30	6	64	34	22	44	83	14	3	.40	.87	.18

EXPLANATION FOR TABLE 4

C/Q -- Ratio of polycrystalline quartzose fragments (mostly chert) to total quartzose fragments.

F -- Total feldspar.

K -- K-feldspar.

L -- Unstable lithic fragments, includes argillaceous-carbonaceous, siltstone, metamorphic, and volcanic fragments.

L_s -- Unstable sedimentary rock fragments.

L_t -- Total lithic fragments, includes unstable lithic fragments and polycrystalline quartz, quartzite, and chert.

L_v -- Volcanic and metavolcanic rock fragments.

P -- Plagioclase.

P/F -- Ratio of plagioclase to total feldspar.

Q_m -- Monocrystalline quartz.

Q_p -- Polycrystalline quartz, quartzite, and chert.

Q_t -- Monocrystalline and polycrystalline quartz, chert, and quartzite.

V/L -- Ratio of volcanic to total unstable lithic fragments.

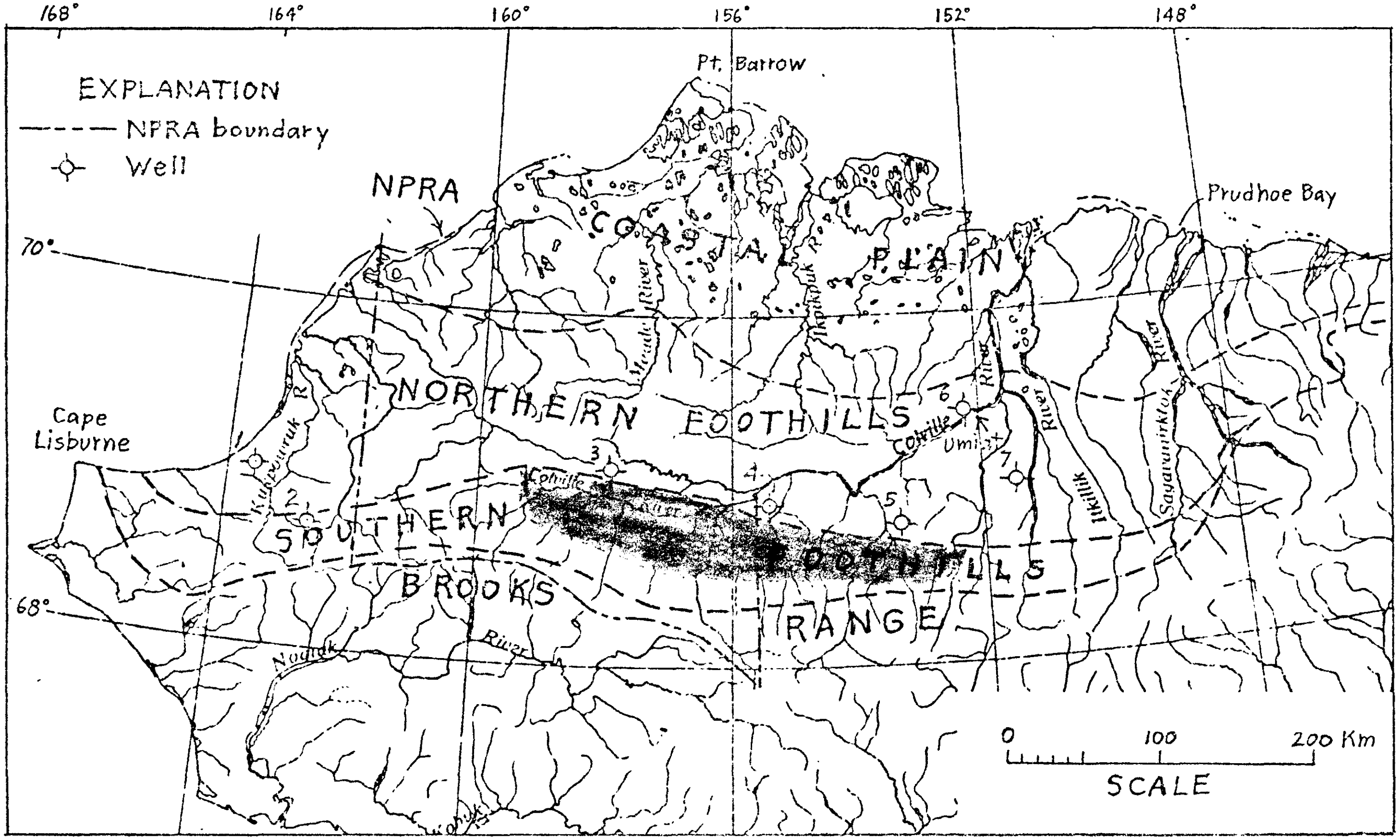

Figure 1.-Index map showing physiographic subdivisions of the North Slope and primary area of investigation (shaded area). Except for a small area near the Kukpowruk River on the far west, outcrops of Fortress Mountain Formation occur only in the Southern Foothills area. Wells shown are those that may have penetrated Fortress Mountain-equivalent strata. From west to east, these wells are (1) Chevron Akulik No. 1, (2) Chevron Eagle Creek No. 1, (3) Awuna No. 1, (4) Texaco West Kurupa No. 1, (5) Texaco East Kurupa No. 1, (6) Seabee No. 1, and (7) Texaco Tulugak No. 1.

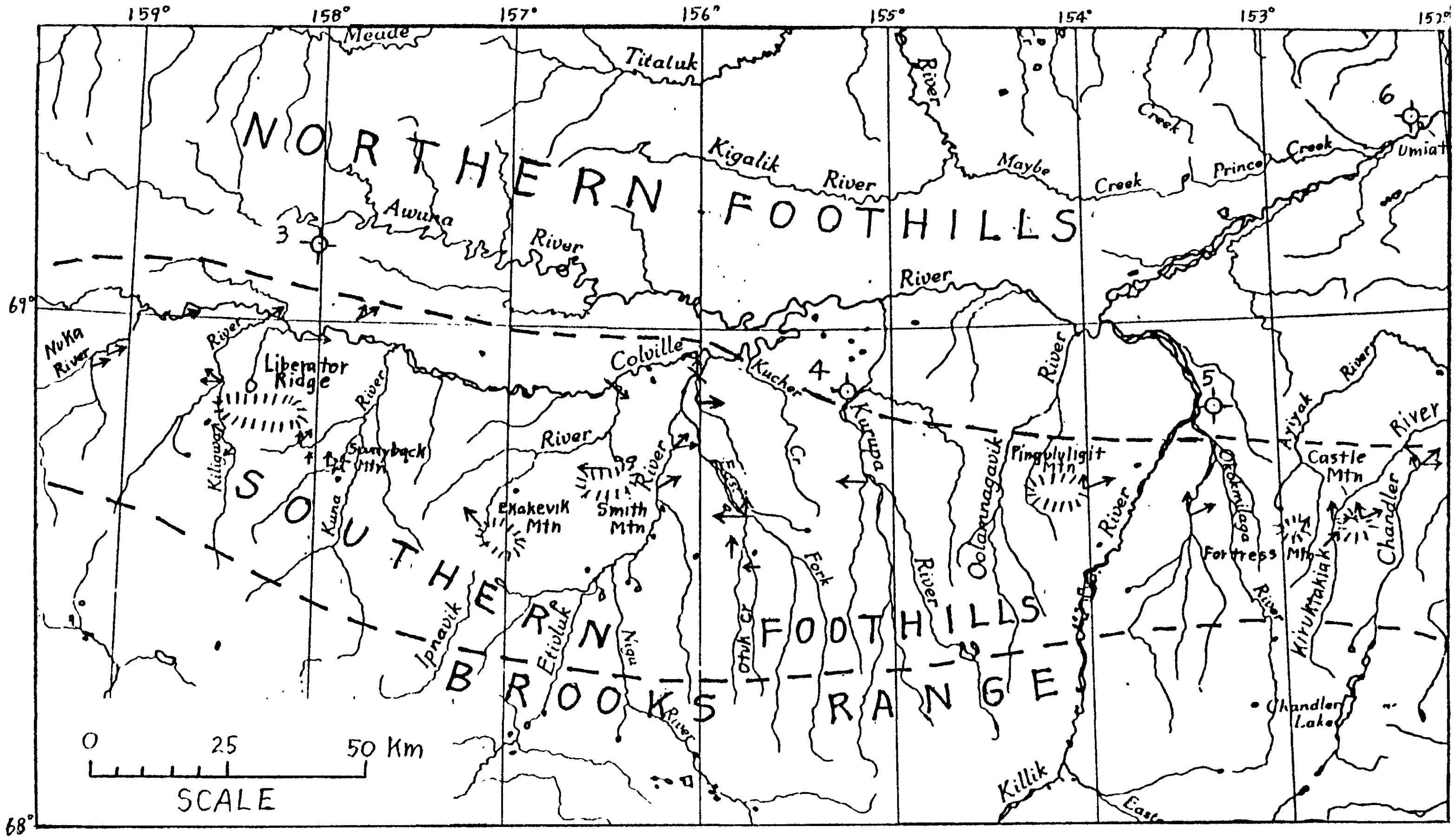

Figure 2.-Index map of primary area of investigation. Arrows indicate paleocurrent directions determined from outcrops of Fortress Mountain Formation; longest arrow of each group indicates predominant direction or most reliable data. Wells shown are (3) Awuna No. 1, (4) Texaco West Kurupa No. 1, (5) Texaco East Kurupa No. 1, and (6) Seabee No. 1.

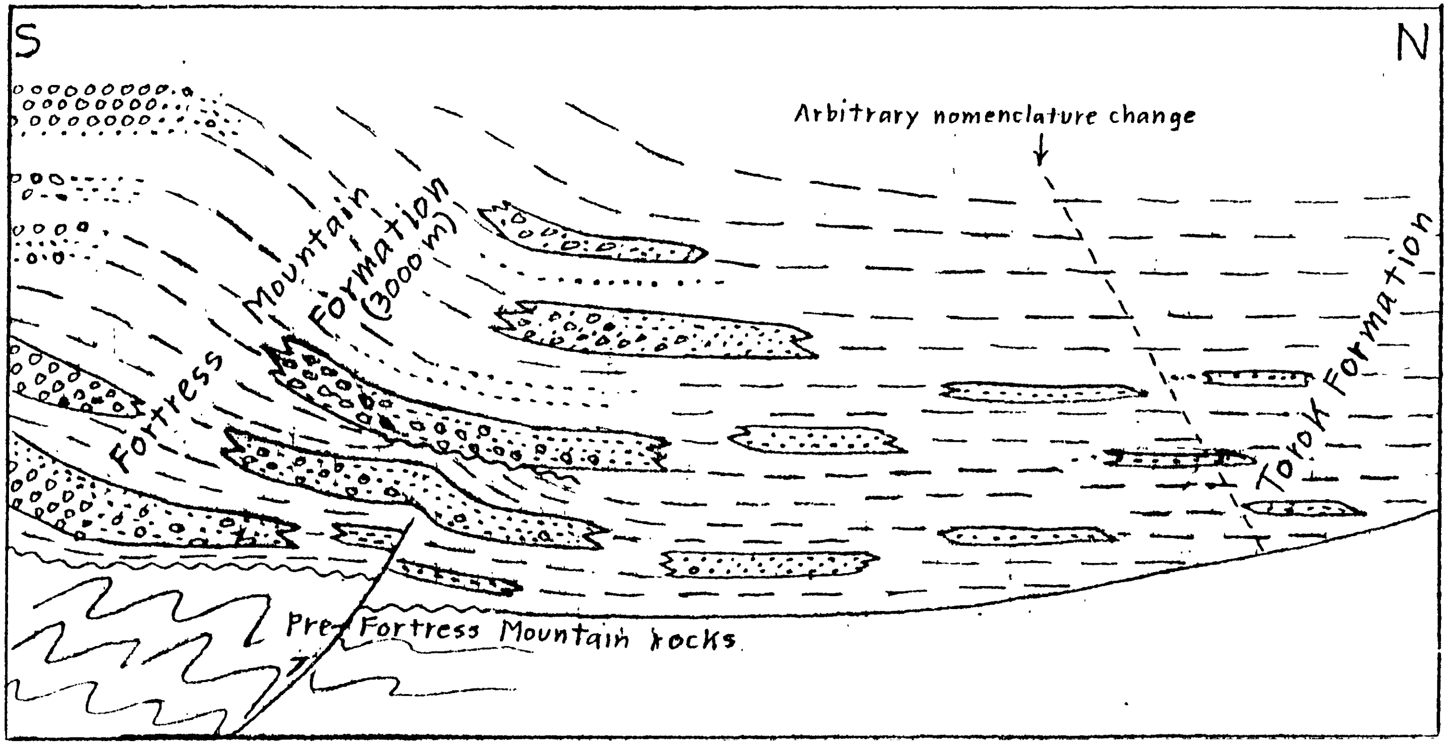

Figure 3.-Conceptual cross section across Southern Foothills showing inferred facies relations of Fortress Mountain and Torok Formations prior to intense folding. Horizontal beds in upper left are alluvial and shallow-marine facies, tilted beds are slope shales and submarine canyon facies, and lower horizontal beds are basinal shale and turbidite facies. No scale intended.

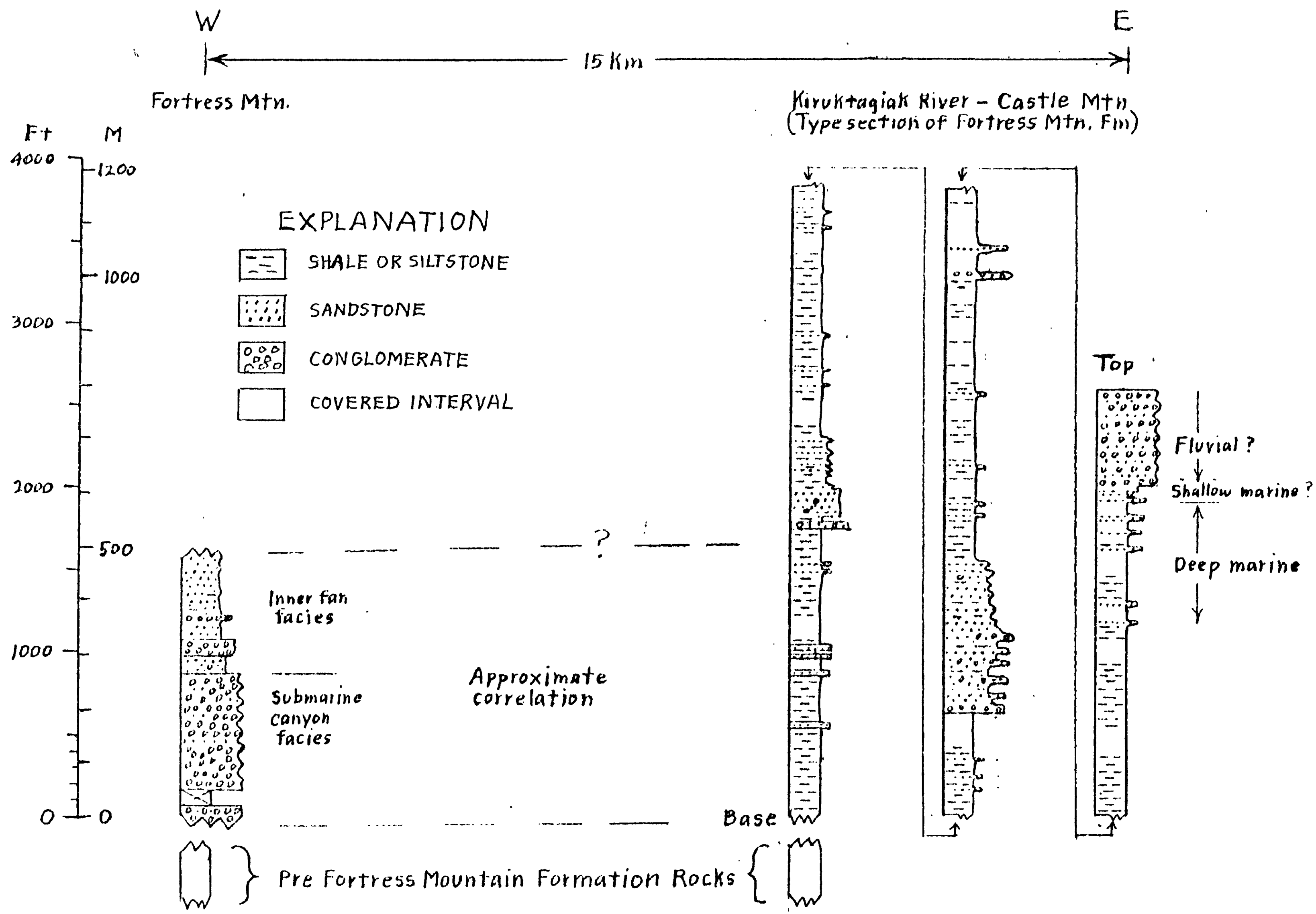

Figure 4.-Inferred correlation of Fortress Mountain Formation between Fortress Mountain and Castle Mountain. Castle Mountain section (type section) modified from Patton and Tailleur (1964).

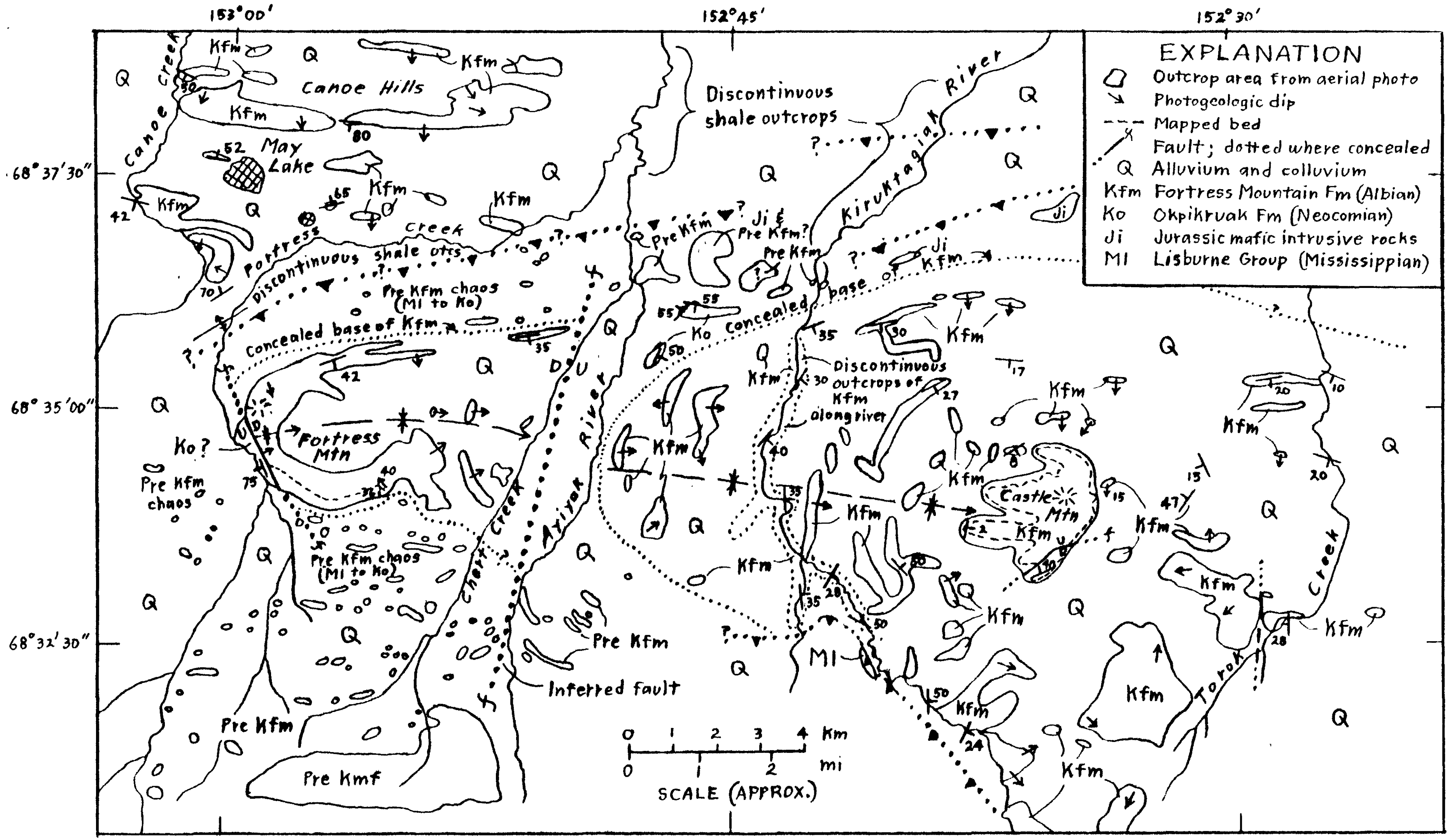

Figure 5.- Geologic map showing discontinuous outcrops and relationships of Fortress Mountain Formation between Fortress Mountain and Castle Mountain (type section of Fortress Mountain Formation). Base map is from aerial photographs. (Geology modified from Patton and Tailleur, 1964.)

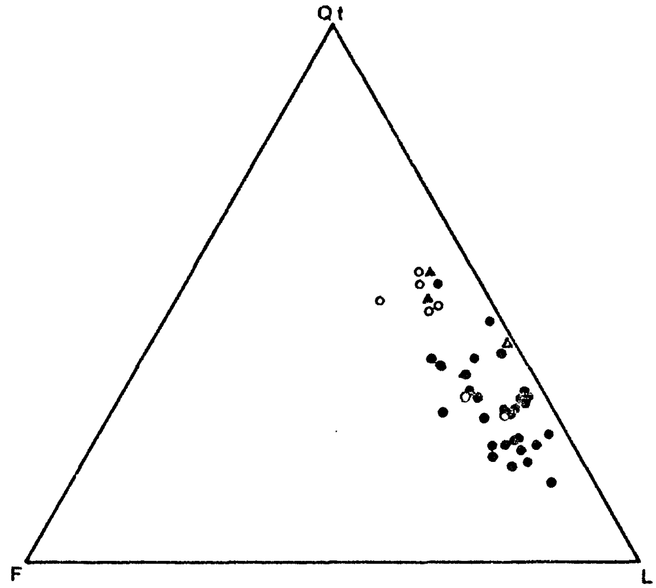

Figure 6.--Triangular QtFL plot showing framework modes with emphasis on grain stability of Fortress Mountain Formation sandstones. Qt is total quartose grains, including monocrystalline and polycrystalline quartz, chert, and quartzite fragments; F is total feldspar; L is total unstable lithic fragments. Circles are samples from the eastern area, and triangles are samples from the western area. Open circles or triangles are fine- to very fine grained samples, and solid circles or triangles are medium- to coarse-grained samples.

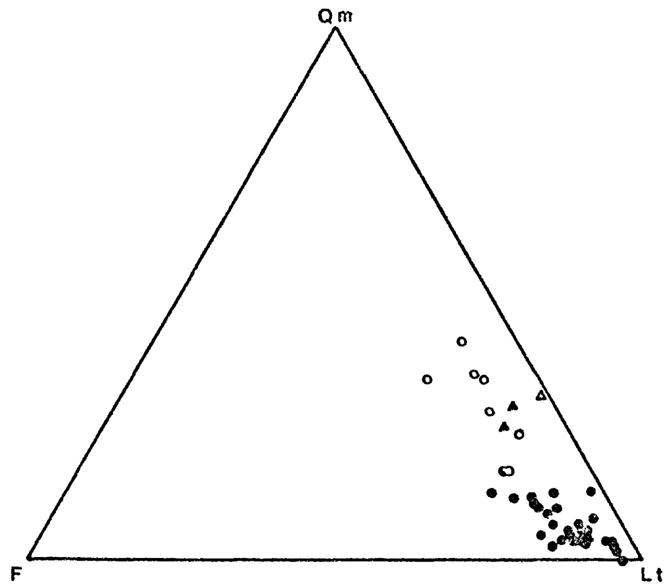

Figure 7.--Triangular QmFLt plot showing framework modes where all lithic fragments, including polycrystalline quartz, chert and quartzite fragments, are grouped with unstable lithic fragments. QM is monocrystalline quartz; F is total feldspar; Lt is total lithic fragments. Circles are samples from the eastern area, and triangles are samples from the western area. Open circles or triangles are fine- to very fine grained samples, and solid circles or triangles are medium- to coarse-grained samples.

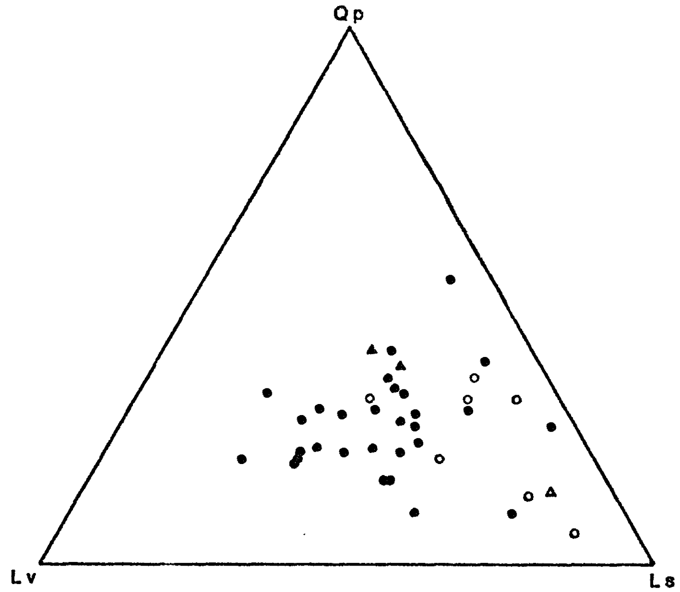

Figure 8.--Triangular QpLvLs plot showing proportions of polycrystalline lithic fragments. Qp is polycrystalline quartzose grains, mostly chert; Lv is volcanic-metavolcanic fragments; Ls is unstable sedimentary rock fragments. Circles are samples from the eastern area, and triangles are samples from the western area. Open circles or triangles are fine- to very fine grained samples, and solid circles or triangles are medium- to coarse-grained samples.

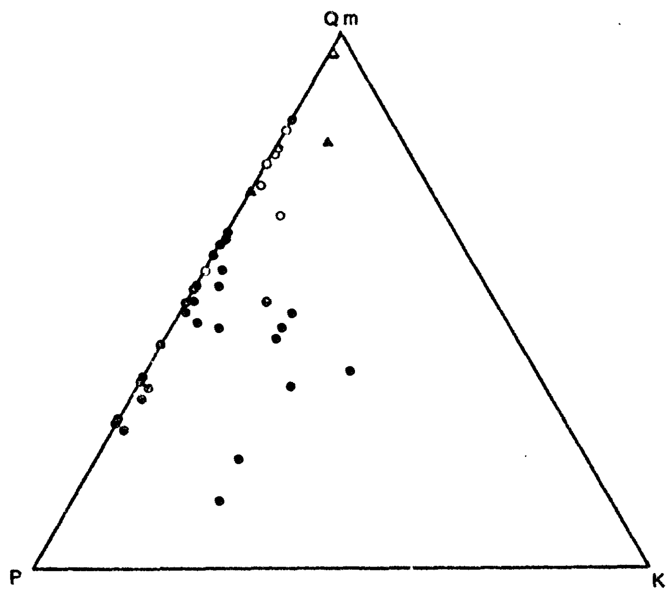

Figure 9.--Triangular QmPK plot showing proportions of monocrystalline framework mineral grains. Qm is quartz grains; P is plagioclase grains; K is K-feldspar grains. Circles are samples from the eastern area, and triangles are samples from the western area. Open circles or triangles are fine- to very fine grained samples, and solid circles or triangles are medium- to coarse-grained samples.