# SUPERPOSED DEFORMATION AND ITS IMPLICATION TO THE GEOLOGIC HISTORY OF THE ELLSWORTH MOUNTAINS, WEST ANTARCTICA

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***Abstract:*** Based on the 1979–1980 field survey, preliminary results of stratigraphic, tectonic, metamorphic, and whole rock K-Ar dating studies of the southern part of the Heritage Range are given. Assembling all the results, the following scheme of a polyorogenic sequence is represented as a first approximation, along with possibilities of some other interpretations. i) The Precambrian events exemplified only by the K-Ar age of 935 Ma are problematically taken for as indicating a fragment of the Precambrian basement. ii) Metamorphic recrystallization under the low grade conditions of WINKLER (Petrogenesis of Metamorphic Rocks, N.Y., Springer, 1974), formation of main cleavages and longitudinal reclined and inclined isoclinal and longitudinal nearly horizontal close folds occurred after the Heritage Group (Middle to Upper Cambrian) and before the intrusion of altered dolerite dikes with minimum ages of *ca.* 400 Ma. These events are referred to either possibly the early Borchgrevink Orogeny, or more probably, the Ross Orogeny. iii) Low grade metamorphic recrystallization, and formation of part of the closely spaced cleavages and longitudinal kink folds occurred after the Crashsite Quartzite (?pre-Devonian to Devonian) and before or during the Whiteout Conglomerate (?Permo-Carboniferous), at around the age of 300 Ma. These events are referred to the late phase of the Borchgrevink Orogeny. iv) Very low grade metamorphic recrystallization, formation of roughly spaced cleavages, longitudinal open folds and transverse gentle folds occurred after the Polarstar Formation (Permian). Maximum K-Ar age of 235 Ma is considered to reflect these events which are referred to the early Mesozoic Ellsworth Orogeny.

## 1. Introduction

The United States Antarctic Research Program sponsored geological survey of the Ellsworth Mountains during the austral summer of 1979–1980, conducting field work from a temporary camp located at about the central part of the mountains (SPLETTSTOESSER and WEBERS, 1980).

The duration of the actual field survey was 38 days during which the Wilson Nunataks, Marble Hills, Liberty Hills, High Nunatak (referred to as the southern area of the Heritage Range), Edson Hills, Soholt Peaks, Webers Peaks (referred to as the central area of the Heritage Range), and small outcrops in the northwestern part of the Heritage Range (referred to as the northwestern area of the Heritage Range) were surveyed (YOSHIDA, 1981a). In these areas, only pre-Mesozoic rocks are found. A one-day flight to Polarstar Peak in the northern Sentinel Range, where the Permian Polarstar Formation crops out, was also made.

This preliminary study summarizes all aspects of investigations done by the writer during and since the 1979–1980 field program. Analysis of field data is still in progress and therefore data and considerations presented in this report are incomplete. Final analysis of the complete orogenic history of the Ellsworth Mountains must be deferred until all field data are systematically analyzed and analyses of the other members of the 1979–1980 geologic research project of the Ellsworth Mountains operation are made available. Nevertheless, a preliminary summary should be of some value.

The polyorogenic view of the Ellsworth Mountains discussed in the last Section was the author's interpretation at the beginning of the field survey. Brief examinations on the deformational sequence of the mountains made during and after the field survey supported this view in some instances. The author's presentation at the Second Symposium on Antarctic Geosciences held in Tokyo in November 1980 (YOSHIDA, 1980) stressed this point. The present article deals with not only the superposed deformation which was presented at the symposium, but also stratigraphy, metamorphism, and K-Ar dating, all of which were examined to include the sequence of the superposed deformation to the polyorogenic view of the Ellsworth Mountains. Part of the outline of this study was reported previously (YOSHIDA, 1981b).

## 2. The Geologic Outline of the Ellsworth Mountains

The geologic outline of the Ellsworth Mountains has been given by a group of geologists from the University of Minnesota, based on 1959–1964 field surveys (CRADDOCK *et al.*, 1964; CRADDOCK, 1969) and partly supplemented and revised by the Norwegian survey of 1974 (HJELLE *et al.*, 1978, 1982). According to CRADDOCK (1969), the stratigraphic succession of the Ellsworth Mountains is summarized as follows, from oldest to youngest. Minaret Group (?late Precambrian)–Heritage Group (?late Precambrian–late Cambrian)–Crashsite Quartzite (?pre-Devonian–Devonian)–Whiteout Conglomerate (?Permo-Carboniferous)–Polarstar Formation (Permian), total thickness being at least 13000 meters. No distinct stratigraphic gap was known except for a probable disconformity at the base of the Polarstar Formation. All the strata show folding with the fold axis paralleling the mountain range associated with synchronous formation of the cleavage and low grade metamorphic recrystallization; all these events were considered to have taken place in around the early Mesozoic. A simplified geologic map after CRADDOCK (1969) and HJELLE *et al.* (1978) is shown in Fig. 1.

The Norwegian party surveyed the southern areas of the Heritage Range and

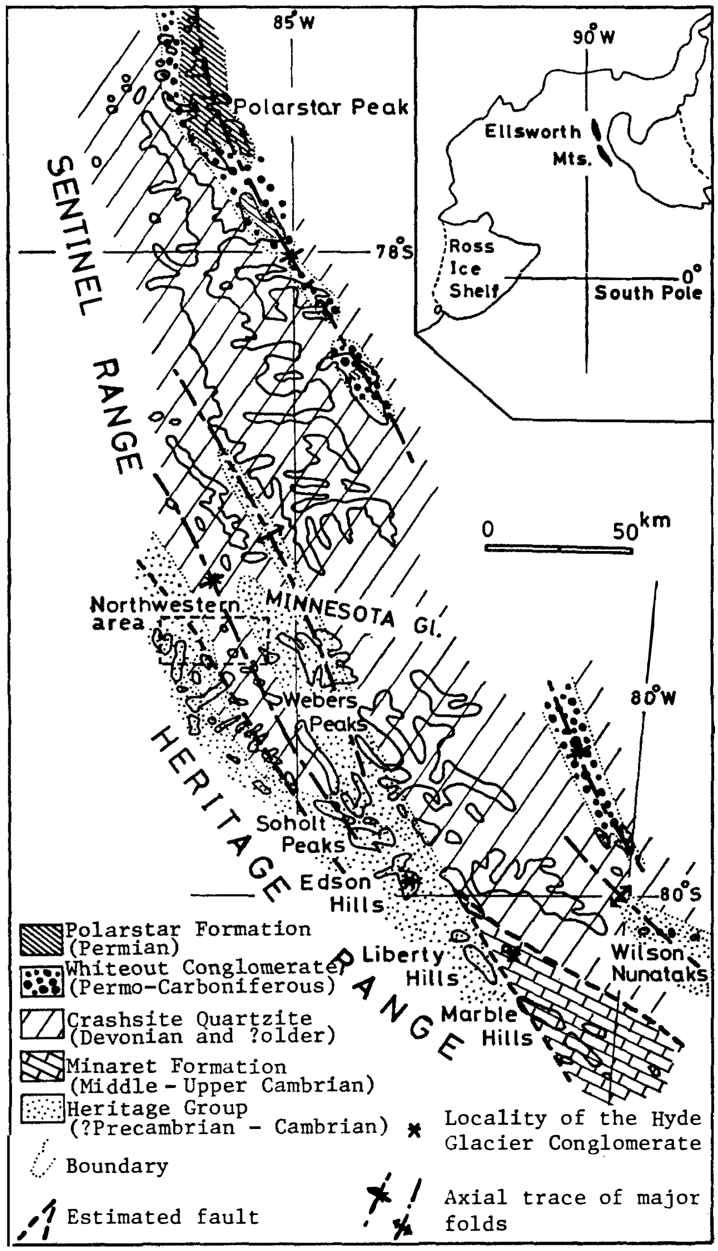


*Fig. 1. Geologic outline of the Ellsworth Mountains (simplified after* CRADDOCK, *1969 and* HJELLE *et al., 1978, with revised stratigraphy) and survey areas.*

revised the stratigraphy, igneous petrology, tectonics, and metamorphism (HJELLE *et al.*, 1978, 1982), their stratigraphy follows, from oldest youngest:

Middle Horseshoe Formation of the lower part of the Heritage Group, corresponding to the upper part of the Minaret Group of CRADDOCK (1969)—Edson

Hills Formation of the upper part of the Heritage Group, corresponding to the lower part of the Heritage Group of CRADDOCK—Dunbar Ridge Formation, corresponding to the upper part of the Heritage Group of CRADDOCK—Crashsite Quartzite—Whiteout Conglomerate; the last two units are the same as those given by CRADDOCK. A clino-unconformity was suggested at the base of the Whiteout Conglomerate, and a major disconformity was pointed out at the base of the Crashsite Quartzite. However, the folding and metamorphic recrystallization were considered to have occurred before, and continued during the deposition of the Whiteout Conglomerate. They have further discussed the petrochemistry of igneous rocks (of pre-Dunbar Ridge Formation) and concluded that the K-alkalic type is dominant and considered that they are of the non-oceanic type and may be the products of an early stage of rift tectonics on a continental crust.

The recent detailed stratigraphic survey by the U.S. team (SPLETTSTOESSER and WEBERS, 1980) appears to have eliminated Minaret Group as Precambrian. The Minaret Formation has been revised to constitute the upper part of the Heritage Group (the revised stratigraphy is shown in Fig. 1).

## 3. Stratigraphy, Tectonics, Metamorphism and K-Ar Dating of the Survey Areas

### *3.1. Stratigraphy*

A Stratigraphic study has been the main emphasis of the U.S. team under G. F. WEBERS, and therefore, the present writer made no systematic survey on this subject. However, the present writer himself observed some stratigraphic evidence, that may have an important role in the analysis of the geologic history. The following section deals mainly with these points; other principal stratigraphic details are left for the previous reports or future studies of WEBERS' team of specialists.

#### 3.1.1. The Heritage Group

This group is the lowermost strata of the survey areas and the Minaret Group of CRADDOCK (1969) is considered to constitute the upper part of the Heritage Group. The Dunbar Ridge Formation of HJELLE *et al.* (1978) is also tentatively included in the upper part of this group. This part of the stratigraphic succession appears to be same as that of the WEBERS' team (SPLETTSTOESSER and WEBERS, 1980). A geologic sketch and cross section of the southern area of the Heritage Range supporting the revised stratigraphy is shown in Figs. 2a and 2b. This interpretation of the geologic structure of the southern part of the Heritage Range has become generally accepted by most members of the 1979–1980 field geologists through their field observations and discussions. The interpretation is based (1) on the stratigraphically upward direction observed at some outcrops in the Liberty Hills and Marble Hills, and (2) on the discovery of trilobite fossil remnant (by J. ANDERSON of a field team including L. ROSEN and the present writer) of possibly Middle or Upper Cambrian (J. POJETA, personal communication at the field camp).

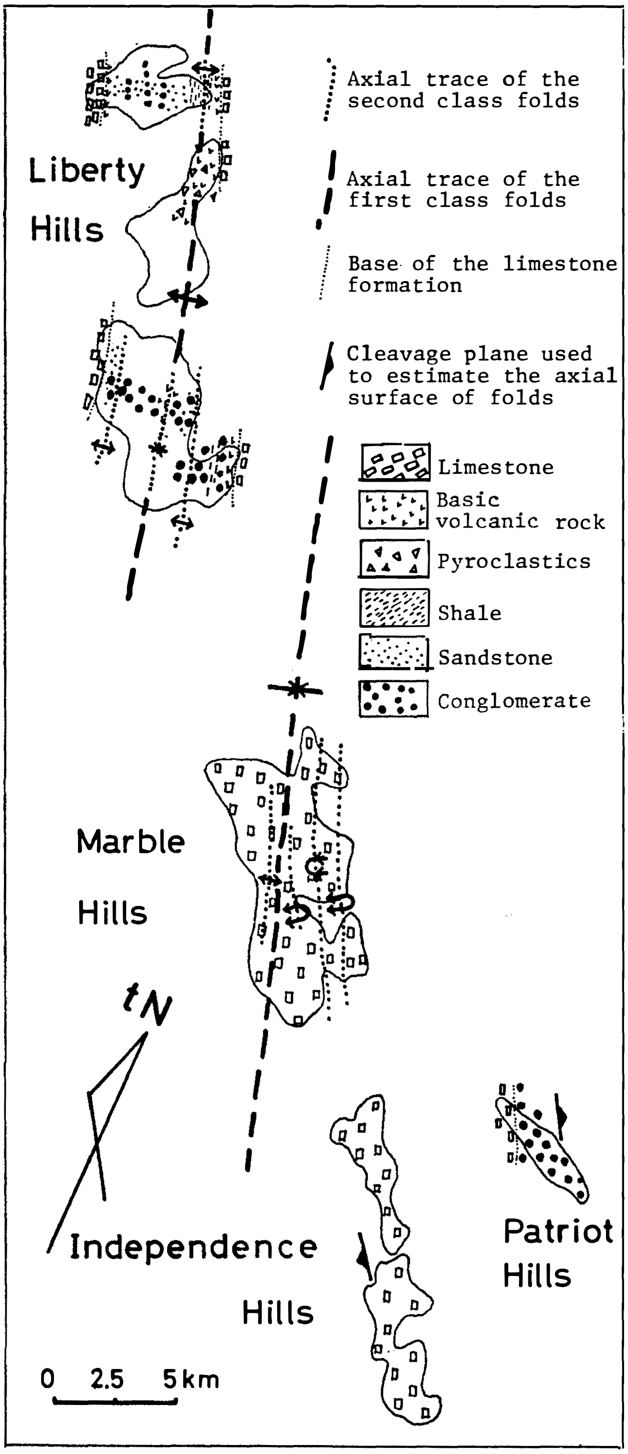
Axial trace of the second class folds
Axial trace of the first class folds
Base of the limestone formation
Cleavage plane used to estimate the axial surface of folds
Limestone
Basic volcanic rock
Pyroclastics
Shale
Sandstone
Conglomerate
Liberty Hills
Marble Hills
Independence Hills
Patriot Hills
N
0 2.5 5km

*Fig. 2a.*

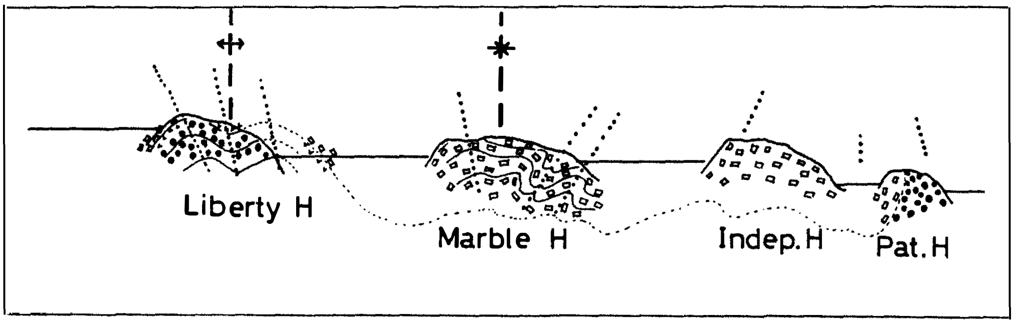


*Fig. 2b*

*Fig. 2. Geologic sketch of the southern part of the Heritage Range (a) and its estimated profile (b). The scale is arbitrary in the profile, where the dotted bars indicate the dip of the main cleavage, which is assumed parallel to the axial surface of second class folds, and thick dashed lines indicate axes of the first class folds in Fig. 2a.*

The Heritage Group is composed of conglomerate, volcanic conglomerate, lavas, pyroclastics, graywacke, tuffaceous shale, and limestone. The limestone composes most of the Marble Hills and locally crops out throughout the southern and central areas. Volcanigenic rocks are abundant in the Edson Hills and High Nunatak, and occur locally in the Liberty Hills. Conglomerate, sandstone, and shale develop more or less throughout the survey areas except the Marble Hills.

3.1.2. The Hyde Glacier Conglomerate

In the northern slope of the 1447-meter-high peak south of the Hyde Glacier, Edson Hills, a conglomerate bed was found to overlie unconformably the strata of the Heritage Group, which there were composed of dark greenish gray graywackes with intercalations of conglomerate. The unconformably overlying conglomerate is characteristically brownish and has a sandy matrix. Pebbles are well rounded and composed of various lithologies. The comglomerate crops out from 1000 to 1400 meters in altitude and is at least some hundreds of meters in east-west diameter as viewed from the ice stream of the Hyde Glacier; the thickness is uncertain. The strata cropping out at higher altitudes are believed to be composed of sandstone, according to binocular observation. These conglomerate and sandstone are termed as the Hyde Glacier Conglomerate in the present article and are tentatively considered to be a different stratigraphic unit from the Heritage Group. Closely spaced cleavage develops on both the Heritage Group strata and the Hyde Glacier Conglomerate rocks, the cleavage being the continuous type at least in the basaltic dikes mentioned below but flaky in all rocks, and hence is believed to be superposed (mentioned later). Basaltic dikes (the Hyde Glacier cleaved dikes) intruding into the Heritage Group strata along the cleavage structure are also overlain by the conglomerate (Figs. 3, 4, 5, Photos 1, 2). A distinct brownish stained zone occurs as a network in the underlying Heritage Group strata. This zone may

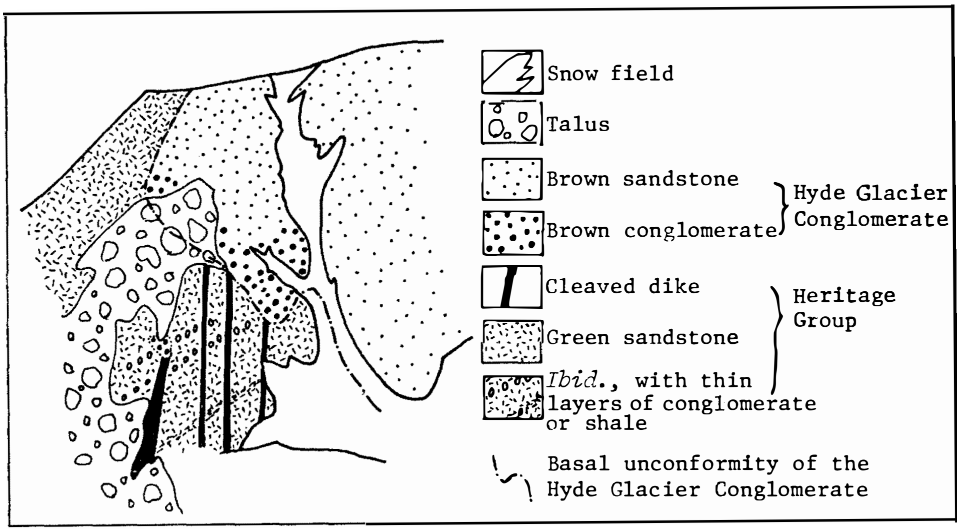


*Fig. 3. Occurrence of the Hyde Glacier Conglomerate at the northern slope of the 1447 meter peak, viewed from the Hyde Glacier (cf. Photo 1). The slope is about 400 meters in hight difference.*

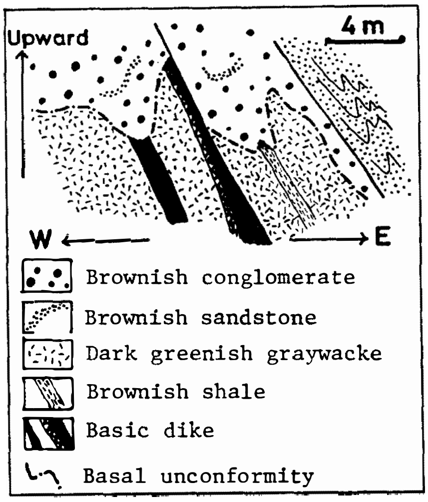


*Fig. 4. Occurrence of the Hyde Glacier Conglomerate at the southern bank of the Hyde Glacier, point 80010506 (cf. Photo 2).*

represent an old weathered zone caused by the surfacial conditions before the deposition of the Hyde Glacier Conglomerate.

A dike-conglomerate, a part of which covers unconformably the Heritage Group strata near the summit of High Nunatak (Fig. 6, Photos 3, 4), is possibly referable to the Hyde Glacier Conglomerate.

Because of the lack of field survey on the distribution of the Hyde Glacier Conglomerate, its stratigraphic position in relation to strata other than the Heritage

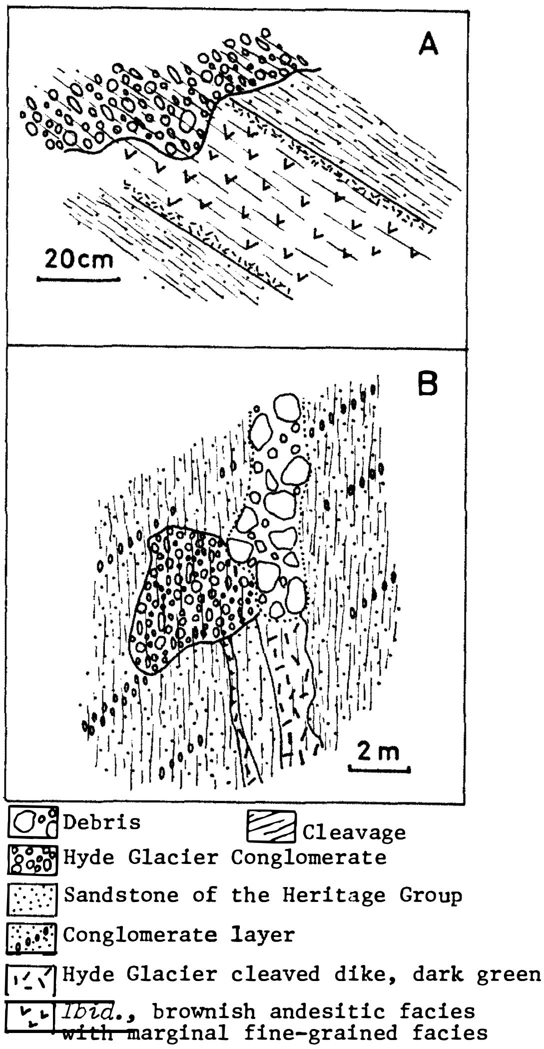


*Fig. 5. Basal unconformity of the Hyde Glacier Conglomerate, at the northern slope of the 1447 meter peak, point 80010801.*

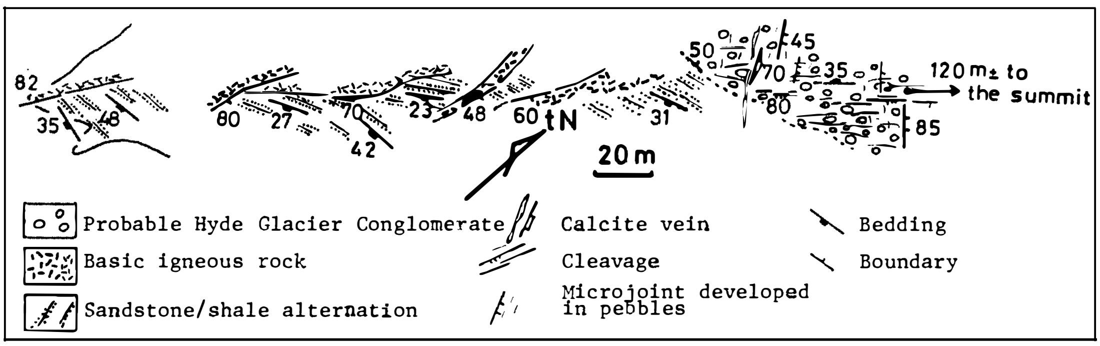


*Fig. 6. Unconformably overlying conglomerate body at High Nunatak (cf. Photo 3).*

Group is uncertain. But it shows at least the closely spaced longitudinal cleavage and consequently apparently predates the Marble Hills Cave Deposits and probably the Heritage altered dolerites which lack the cleavage structure. The Hyde Glacier Conglomerate may either postdate the Heritage Group or have formed in the later period of its accumulation. If the latter is the case, the Heritage Group may be divided into two groups by the basal unconformity of the Hyde Glacier Conglomerate, and considerable portions of the former Heritage Group may be included in the upper group; further systematic analysis of stratigraphy is needed on this point. According to G. F. WEBERS, however, the stratigraphic position of the Hyde Glacier Conglomerate is well known based on his stratigraphic surveys around the Edson Hills area; the Hyde Glacier Conglomerate may be a cut-and-fill sedimentary structure formed by a channel of sand and gravel through other deltaic sediments which were deposited essentially at the same time (WEBERS, personal communication). WEBERS' suggestion should not be neglected, because he made a plentiful and detailed stratigraphic survey. But because of characteristic occurrence of the Hyde Glacier Conglomerate which appears somewhat difficult to be explained as the closs-and-fill sedimentary structure, the author prefers not to abandon the interpretation of the Hyde Glacier Conglomerate as a distinct stratigraphic until he will examine the field data of WEBERS.

3.1.3. The Crashsite Quartzite

The Crashsite Quartzite was observed at Webers Peaks and in the northwestern area of the Heritage Range. This formation is composed of quartzite and quartzitic sandstone intercalated with thin layers of mudstone. The base of the Crashsite Quartzite could not to be determined from the present study. At the northeastern ridge of Springer Peak, where the Crashsite Quartzite crops out in continuation from the Heritage Group (Fig. 7), the two units appear to be conformable as suggested by CRADDOCK (1969). But it depends on the location of

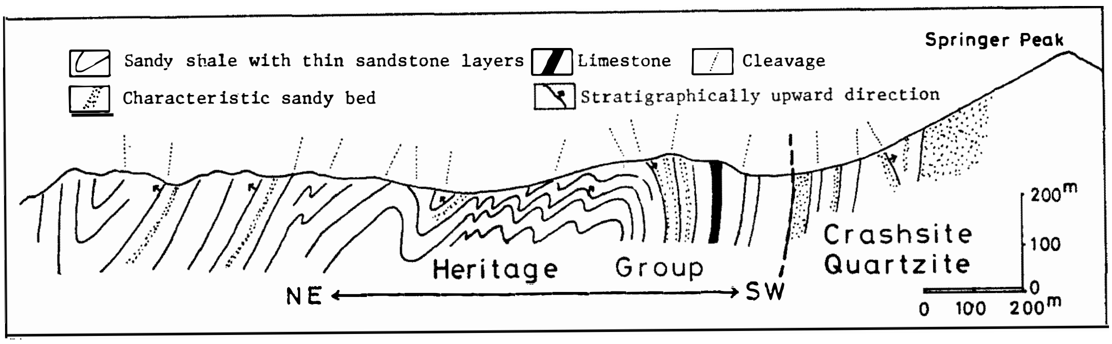


*Fig. 7. Estimated geologic profile of the eastern ridge of Springer Peak, Webers Peaks. The boundary between the Heritage Group and the Crashsite Quartzite (thick dashed line) is referred to the description after CRADDOCK (1969) (for more explanation, see text).*

the boundary of the two groups. If the boundary lies 140 meters southwest of a limestone layer as mentioned by CRADDOCK (1969), strata of the Heritage Group, some hundreds of meters thick, disappear in the southwestern wing of the anticlinorium (*cf*. Fig. 7) and some stratigraphic or tectonic gap at the boundary, or possibly some longitudinal reverse faults probably at the anticlinorium, should be considered. HJELLE *et al.* (1982) suggested that there may be some stratigraphic break such as a disconformity at the base of the Crashsite Quartzite, from the variations in lithofacies and thickness of the underlying strata. The limited distribution of the Hyde Glacier Conglomerate appears to agree with their supposition.

3.1.4. The Whiteout Conglomerate and the Polarstar Formation

These strata were not observed in the survey areas. The Whiteout Conglomerate is composed of mainly conglomerate and the Polarstar Formation consists of silty argillites intercalated with graywackes (CRADDOCK, 1969). A one-day flight to Polarstar Peak provided brief observations throughout the Sentinel Range and sampling of rocks of the Polarstar Formation near Polarstar Peak, but no stratigraphic data was obtained.

A clinounconformity was suggested at the base of the Whiteout Conglomerate by HJELLE *et al.* (1978, 1982) from the local absence of the upper part of the Crashsite Quartzite as well as from the general distribution of the weathered zone at the uppermost horizon of the Crashsite Quartzite in the Heritage Range. CRADDOCK *et al.* (1964) estimated a disconformity at the base of the Polarstar Formation.

3.1.5. The Marble Hills Cave Deposits

Limestone breccia bodies composed of angular to subangular blocks of limestone and interstitial calcareous material without a trace of cataclasis sporadically develop throughout the higher ridges of the Marble Hills (Photos 5, 6). CRADDOCK *et al.* (1964) described these breccia bodies in some detail, reporting that they occur in the Marble Hills and northward to the Union Glacier.

The breccia body unconformably overlies the steeply dipping or folded stratified limestone of the Heritage Group, or cutting them bounded by a longitudinal fault. The limestone blocks have cleavage structures of differing intensities and orientations by each. The interstitial matrix is generally white to dark brown massive calcareous material, and in some cases, a zonal growth of carbonate minerals similar to a cavity filling. In the southern part of the Marble Hills (at the "Fold Cliff" mentioned later), the matrix of the breccia body is composed of dark brown sandy limestone without the longitudinal cleavage structure but bearing faint cleavage paralleling the periphery of the blocks and a distinct graded bedding structure. The bedding plane of the matrix is not reversed (younging upward) and gently dips southeast although the surrounding stratified limestone moderately dips southwest.

The present writer tentatively interprets these breccia bodies to be cave deposits judging from their mode of occurrence and lithology. Time of deposition is uncertain, although the deposits postdate the upper part of the Heritage Group. Some of the longitudinal folding of the Heritage Group and main cleavage formation also predate the cave deposits. Some of the longitudinal faults, possibly associated with some of the longitudinal folds, however, postdate or are synchronous with the cave deposits.

*3.2. Folds, faults and cleavages*

Rocks of the Heritage Range exhibit various kinds of fold and cleavage structures. Faults are also common, some of which are accompanied by folds or cleavages. A simplified projection of axial surfaces and hinges of various folds exemplified from data obtained in the southern to central areas is shown in Fig. 8.

3.2.1. The inclined folds

Second class to small scale reclined to inclined plunging isoclinal folds with

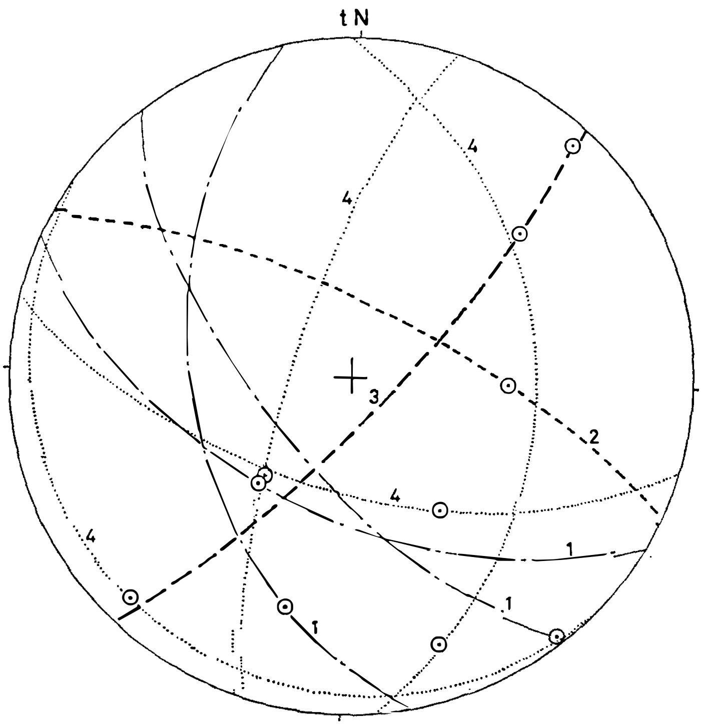


*Fig. 8. Schematic stereographic projection of fold surfaces and hinges of all folds, from field data at Marble Hills and Soholt Peaks. Great circles indicate axial surfaces and circles with a dot denote their hinges. Numbers 1–4 on the great circles are as follows. 1: Inclined fold and longitudinal close folds. 2: Longitudinal open folds. 3: Transverse gentle folds. 4: Small kink folds. The figure is a Schmidt net, lower hemisphere projection; all other figures with stereographic projections are in the same direction hereafter.*

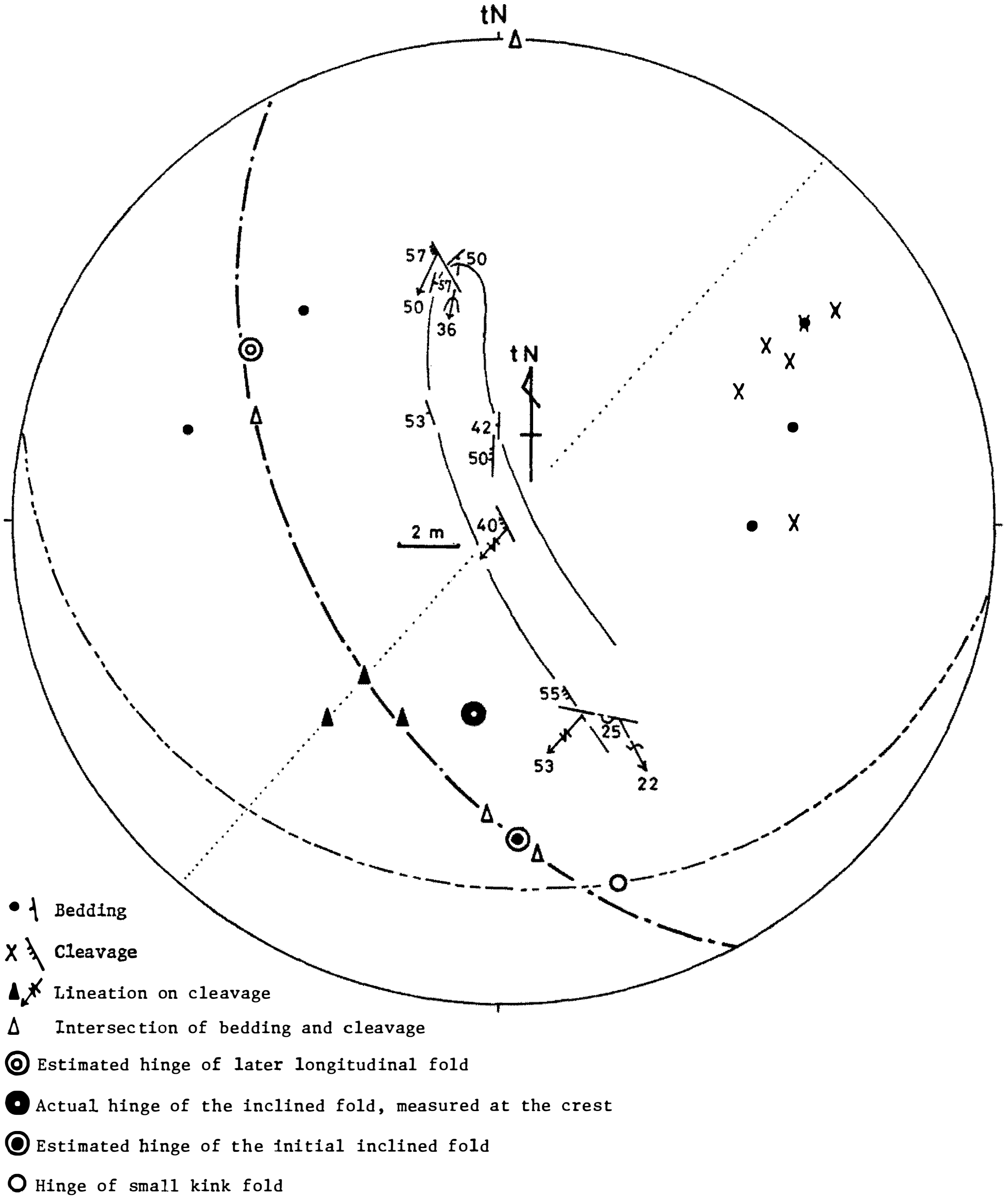


*Fig. 9. Stereographic projection and sketch (horizontal projection) of the reclined fold at Marble Hills (point 79121501). Great circles denote axial surfaces as follows. Dashed line with a dot: mean axial surface of the reclined fold. Dashed line with two dots: later small kink fold. Dotted line: later transverse fold and crenulation cleavage inferred from lineations.*

their axial traces paralleling or subparalleling the mountain range (hereafter referred to as the longitudinal trend) were found sporadically in the Marble Hills and Edson Hills (Fig. 9, Photo 7). These folds are believed to be refolded by the longitudinal close and open folds. These folds are referred to as the inclined fold in the sense of RICKARD (1971).

3.2.2. The longitudinal close folds and associated structures

Many second class to small scale tight to close (classification of fold style by the interlimb angle is referred to that of FLEUTY, 1964) folds with axial surfaces trending parallel or subparallel to the mountain range and inclined moderately to steeply northeast or southwest with gentle or nearly horizontal plunges develop throughout the southern and central areas. At the southern cliff of the central massif of the Marble Hills which the field team called "Fold Cliff", and at two eastern ridges of the Liberty Hills, the entire cross sections of the mountain range show continuous folding structures (Fig. 10, Photo 8). In the Edson Hills, Soholt Peaks, Webers Peaks, High Nunatak, and western and eastern marginal zones of the northwestern area, the overall geologic structure is generally moderate to steep and monoclinic (homoclinal), and second class tight to close folds are found only locally; the overall development of the fold structure may be the case. These folds are referred to as the longitudinal close folds.

In the northwestern area, a considerable part of the central zone of the area occupied by the Crashsite Quartzite is characterized by the horizontal or gently dipping flat structure and the moderate to steep structure is dominated in the western and eastern parts of the area where the Heritage Group crops out. Second class longitudinal kink folds develop sporadically throughout the area. Their axial surfaces are generally steeply inclined northeast or southwest; the variation of the inclination is somewhat systematic, which may be explained either by the refolding of the longitudinal kink fold by the longitudinal open folds or by being a box type of the kink fold itself. In a cliff north of the Webster Glacier, a box-type set of development of the kink folds were found locally (Fig. 11, Photo 9). These folds are referred to as the *longitudinal kink folds*. All the folds described above are referred to as the longitudinal close folds in this article, although they appear to be further chronologically classified as mentioned later.

The *major folds* paralleling the mountain range may be interpreted from the distribution pattern of the Crashsite Quartzite among the Heritage Group exemplified in a geologic map (Fig. 1, cited after CRADDOCK, 1969). Structure of the Heritage Group at the eastern side of the northwestern area is conformable to the estimated major syncline. But the major fold structure itself was not ascertained, and furthermore, the Crashsite Quartzite exhibits a flat structure at the trough of the estimated syncline near Welcome Nunatak and Landmark Peak. It is probable that either the major fold structure is a box type in large scale or the distribution of the Crashsite Quartzite is governed by the longitudinal fault system. Whatever it

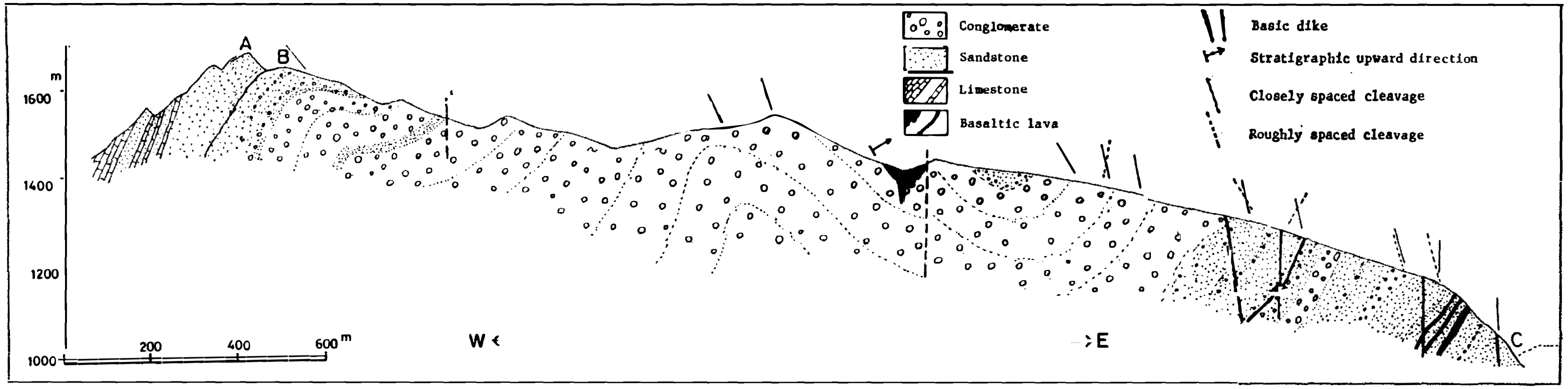


*Fig. 10.* *Geologic profile of the Liberty Hills, indicating continuous development of the longitudinal folds. Axial surfaces of folds are arbitrarily assumed to parallel the closely spaced cleavage. A: Summit of the peak. B: Junction of the ridge. C: Foot of the ridge. (Along the eastern ridge of a peak between Sponholz Peak and Kelley Peak).*

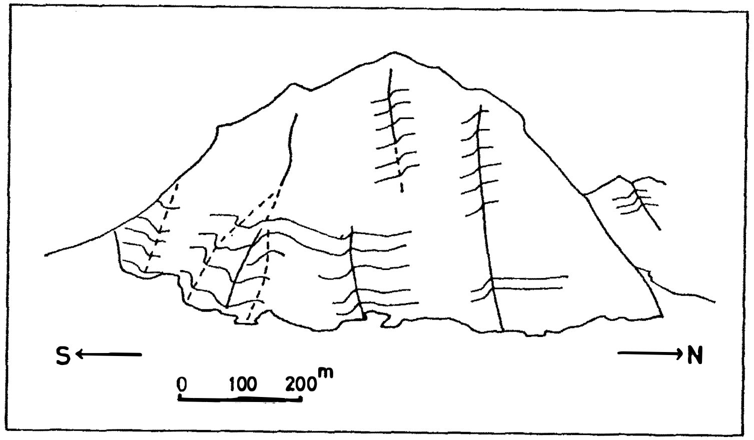


*Fig. 11.* *Longitudinal kink fold at the eastern slope of the northern part of Frazier Ridge, viewed from the Webster Glacier (cf. Photo 9). Full lines along the axial traces indicate small faults or fractures, and dashed lines denote axial traces.*

may be, this megascopic longitudinal structure is evident as the major structure throughout the Ellsworth Mountains, as indicated by CRADDOCK *et al.* (1964) and CRADDOCK (1969).

*Longitudinal thrust faults* with small displacements are locally associated with the longitudinal close folds and are typically developed at "Fold Cliff" of the Marble Hills. Closely spaced to continuous (classification of cleavage is referred to that of POWELL, 1979) rock cleavage structures are well developed in rocks where longitudinal close folds develop or are estimated to develop. They are called the *main cleavages*. Conjugate sets of shear fractures with acute bisectrix normal to the cleavages and the intersecting lines generally in the dip direction develop mainly in the northwestern area, but extension cracks or shear fractures restricted in the muddy augens in limestone or in pebbles in conglomerate develop throughout the southern areas (Photos 10, 11).

Some of the longitudinal faults mentioned above were found to cut the Marble Hills Cave Deposits. Since the cave deposits are evidently later than the main cleavage formation, at least some of the longitudinal faults might have moved until after the main cleavage formation, or some of the longitudinal folds associated with the longitudinal faults might have been formed later than the main cleavage.

3.2.3. The longitudinal open folds

Second class to minor longitudinal (striking around N50°W) open folds with nearly vertical axial surfaces were found in the clastic strata of the easternmost nunatak of the Wilson Nunataks (Fig. 12, Photo 12). In this outcrop, psamitic rocks represent roughly spaced cleavages paralleling the axial surface of the folds, but intercalated mudstones have flaky but closely spaced cleavage on the same strike as, the axial surface, but showing a divergent fan. In the other nunataks of the Wilson Nunataks, fine clastic rocks with a main cleavage composed of continuous or closely spaced cleavage structure with various strikes are cut by a massive dolerite dike of the Heritage altered dolerites. There the roughly spaced cleavage with a strike of N50°W is developed sporadically in both the country clastic rocks and the dolerite (*cf.* Fig. 17). Thus the open folds described above appear to be later than the main cleavage and hence later than the longitudinal close folds. These folds are referred to as the longitudinal open folds in this article and the associated cleavages are called the *roughly spaced cleavages*.

Superposition of the roughly spaced cleavages over the closely spaced cleavages, or the closely spaced cleavages over the continuous cleavages are common throughout the southern to central areas of the Heritage Range (Fig. 13). It is therefore possible to assume that some folds such as the longitudinal open folds detected in the Wilson Nunataks also develop throughout the southern to central areas.

Continuous open to chevron folds and discontinuous kink, overturned to recumbent folds were observed in the northern part of the Sentinel Range (Photos

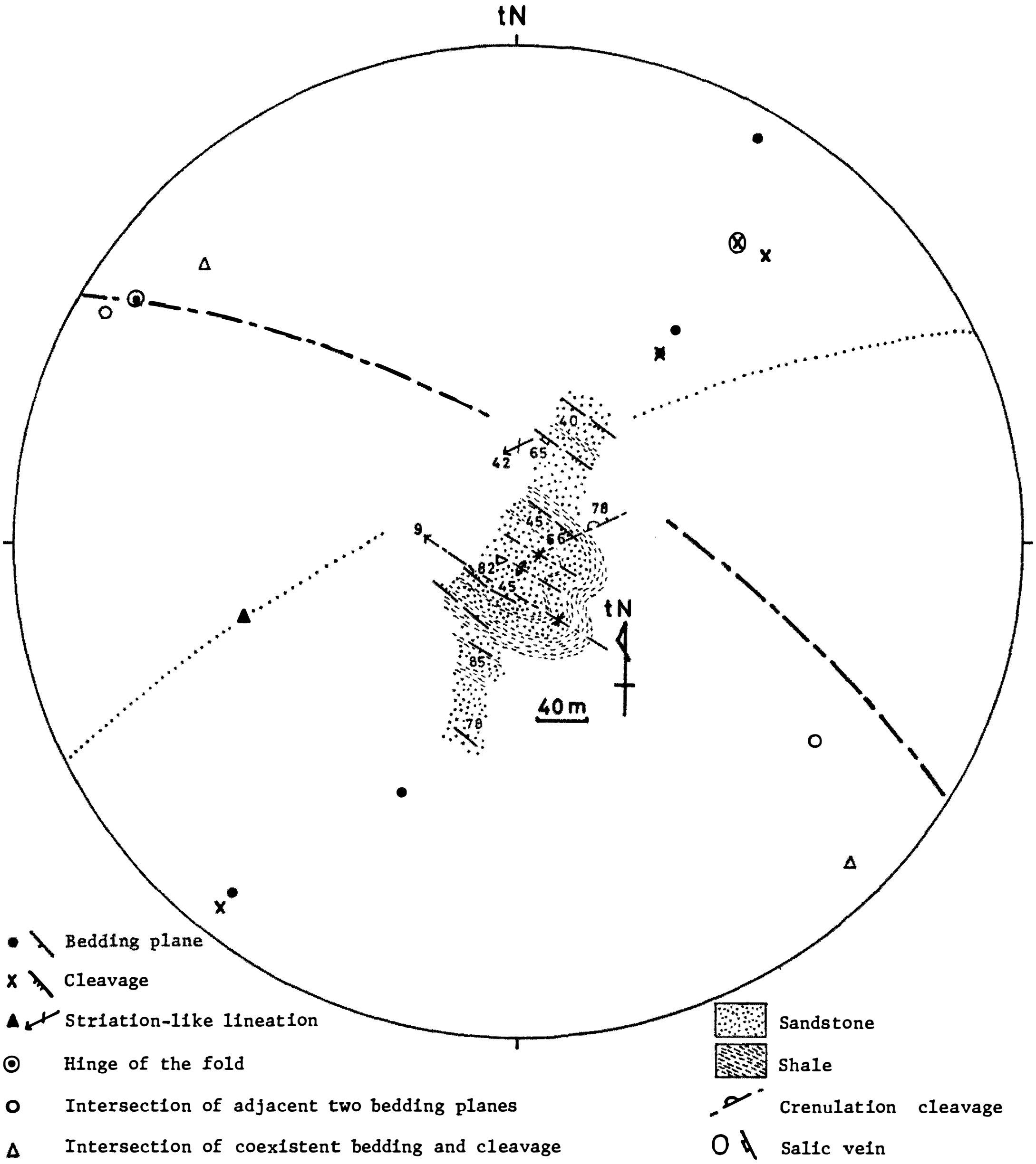


*Fig. 12. Stereographic projection and sketch (horizontal projection) of the longitudinal open fold at the eastern-most nunatak of the Wilson Nunataks (cf. Photo 12). Great circles indicate axial surfaces as follows. Chain: axial surface of the open fold. Dotted line: crenulation cleavage and axial surface of the estimated transverse fold.*

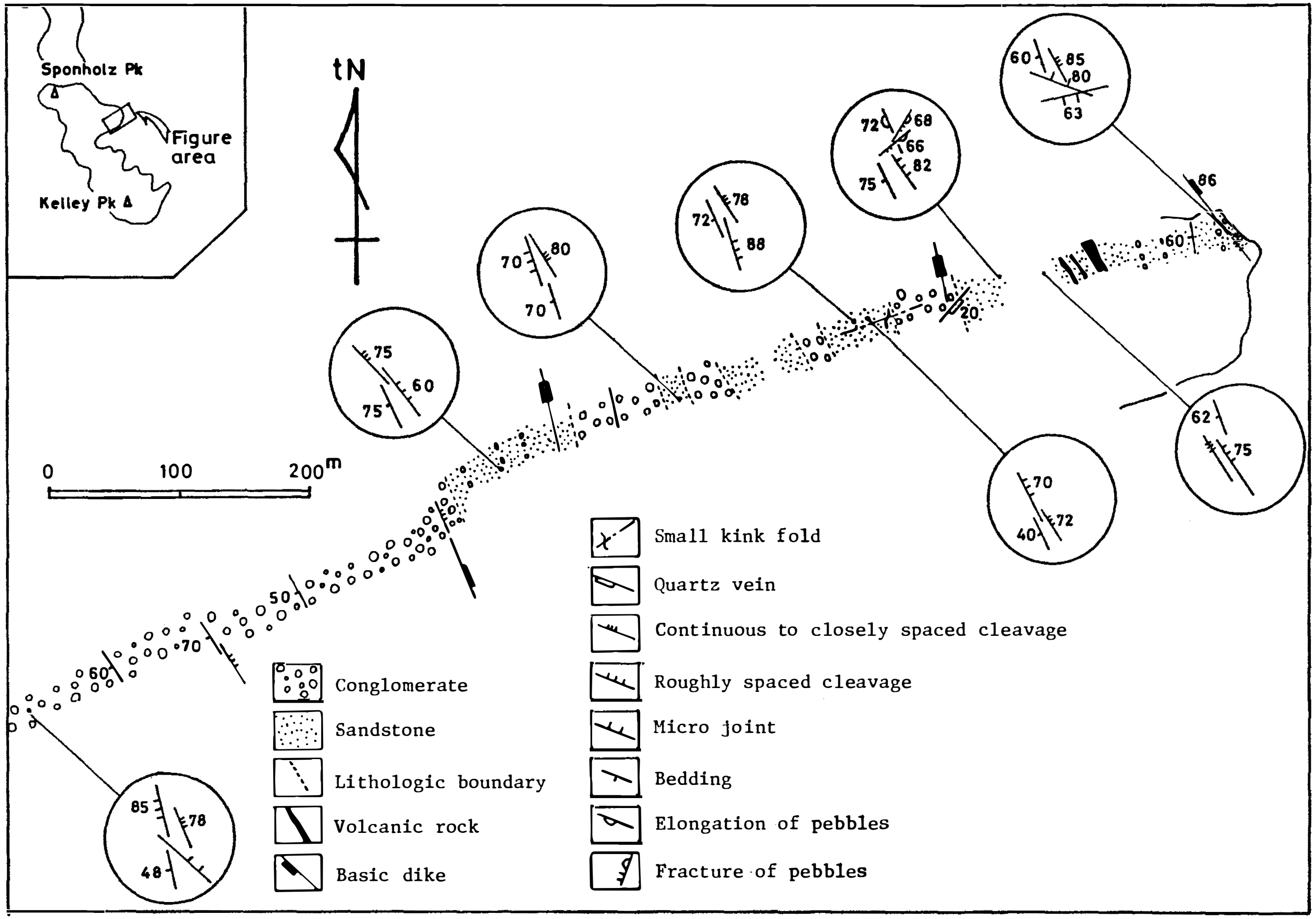


*Fig. 13. Example of the development of superposed cleavages at the eastern ridge of the Liberty Hills (cf. Fig. 10).*

13, 14) where the Polarstar Formation crops out. Near Polarstar Peak in the northern part of the Sentinel Range, both the sandstone and shale exhibit faint cleavage or microjoint structures striking parallel to the mountain range and dipping nearly vertical (Photo 15). CRADDOCK *et al.* (1964) mentioned that all strata including the Whiteout Conglomerate and the Polarstar Formation exhibit folding and cleavage in the same orientation as is found in the underlying formations. HJELLE *et al.* (1978, 1982) pointed out a distinct difference in style and intensities between the folds developed in the unites below the Whiteout Conglomerate and in those developed in the Whiteout.

All the folds observed in the Sentinel Range may either be referred to the longitudinal close folds or more probably, to the longitudinal kink folds or the longitudinal open folds.

3.2.4. The transverse gentle folds

Second class transverse gentle folds are believed to develop throughout the northwestern area of the Heritage Range, judging from the systematic variation of the plunge of hinges of the longitudinal close folds (Fig. 14). A similar structure

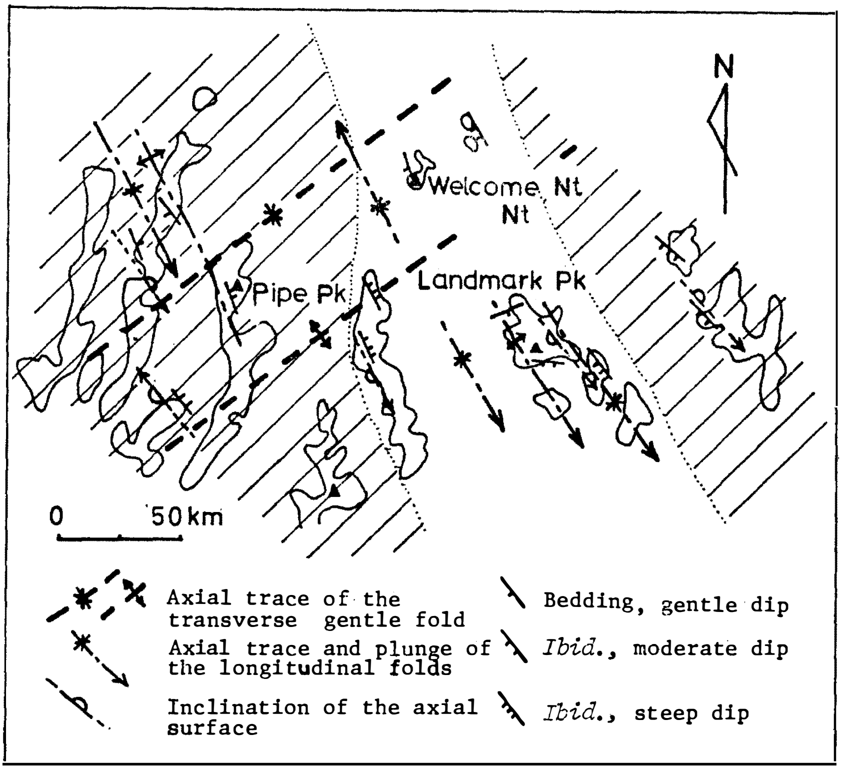


*Fig. 14. Transverse gentle folds in the northwestern area. The gentle fold is estimated from the systematic variation of plunges of hinges of longitudinal folds.*

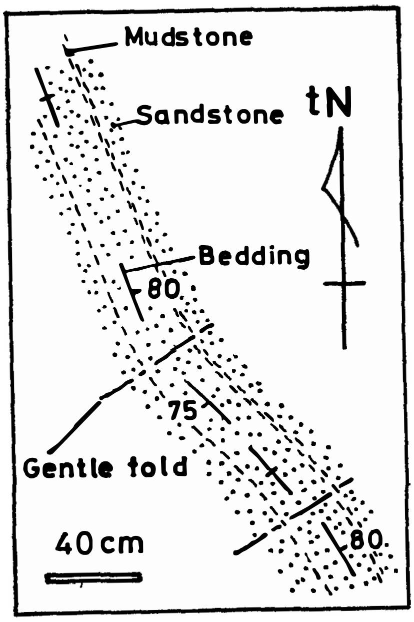


*Fig. 15. Transverse small gentle fold at the eastern ridge of Springer Peak, Webers Peaks.*

is also probable in the central and southern areas because plunge of the hinges of the longitudinal folds in these areas varies in some extent. These folds are referred to as the transverse gentle folds in this article.

*Crenulation cleavages* develop locally on strongly cleaved rocks in the southern to central areas and gentle small folds were also found locally (Fig. 15, Photo 16). Both of the axial surfaces of the gentle small folds and the crenulation cleavages are transverse and vertical. Since the trend of these structures is generally similar to the transverse gentle folds mentioned above, these small structures are considered to be cogenetic with the transverse gentle folds.

3.2.5. Small kink folds

Small kink folds of various trends are not rare in the southern Heritage Range (Photo 17). The orientations of their axial surfaces are generally gently inclined, and some form pairs of the conjugate set. Small gentle folds and kink folds with gently inclined axial surfaces were found locally throughout the Heritage Range. They are referred to as the small kink folds in this article. These folds apparently refold the inclined folds (*cf.* Fig. 9), some of the longitudinal close folds, and main cleavages. No chronological relationship with the other folds was detected. These folds are probably referred to the small folds related to some other larger scale folds. Many of the axial surfaces of the small kink folds strike in the transverse direction and are probably related to the transverse gentle folds, and some others strike in the longitudinal direction and may be related to some of the longitudinal folds. Only a small number of the kink folds, however, strike in different directions and are difficult to relate to larger scale folds.

*3.3. Intrusive igneous rocks*

Abundant basic intrusive rocks and a small number of acid dikes crop out in some parts of the southern and central areas. The Hyde Glacier cleaved dikes and the Heritage altered dolerites are the main groups among them.

3.3.1. The Hyde Glacier cleaved dikes

Several basaltic to andesitic dikes crop out on the northern slope of ridges on the south side of Hyde Glacier, Edson Hills, intruding into the Heritage Group, and are unconformably overlain by the Hyde Glacier Conglomerate (*cf.* Figs. 3, 4, 5, Photos 1, 2). These dikes are some tens of centimeters to some meters wide, intruding either parallel to or inclined from the cleavage structure of the country rocks, but possessing distinct continuous and flaky cleavage structure paralleling that of the country rocks. A fine-grained marginal (chilled) facies develops in some of these dikes, the marginal facies is generally more intensely cleaved and

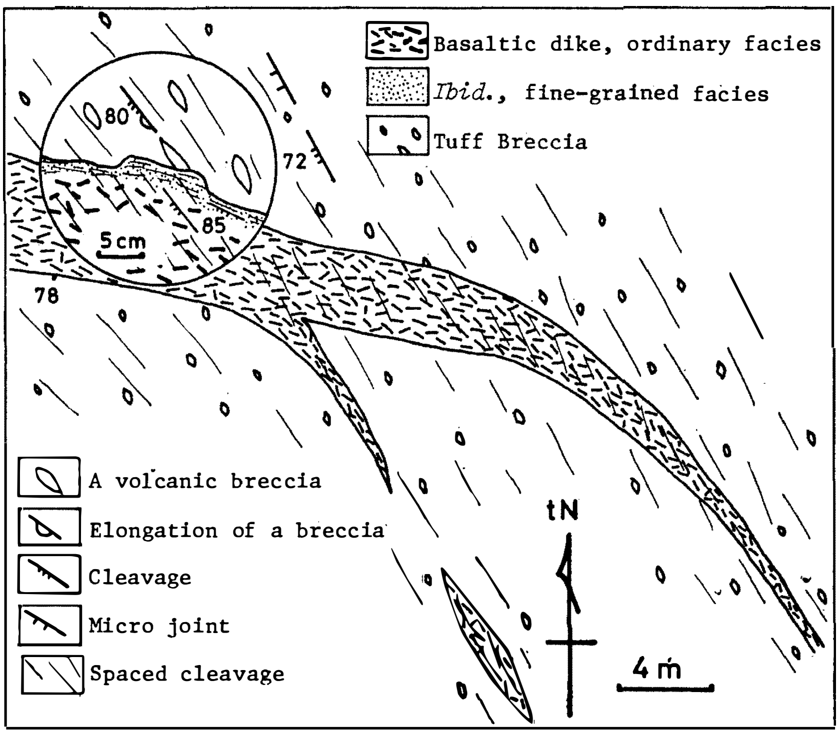


*Fig. 16. Evidence showing the formation of cleavage prior to dike emplacement, at the southern bank of the Hyde Glacier, point 80010510. The thick part of the dike traverses the cleavage cutting elongate volcanic breccia of the country tuff breccia. At the thinner terminus of the dike, its trend becomes parallel to the cleavage of the country rock. Since the dike itself represents cleavage structure parallel to the country rock, the cleavage formed twice.*

more quartz-dominant than the central coarser-grained facies. Some folded or transposed basic dikes develop in the lower reaches of the Hyde Glacier; these may also belong to the Hyde Glacier cleaved dikes. The K-Ar ages of these dikes, 237 and 254 Ma, are too young, probably because of the later metamorphism as mentioned later. In areas from western Queen Maud Land to the Shackleton Range, intrusive dolerites with K-Ar ages of 452 to 580 Ma are known (CRADDOCK, 1970; REX, 1972). The older group of these dolerites may possibly be referred to the Hyde Glacier cleaved dikes.

The parallel intrusion of the dikes to the cleavage structure of the country rocks should be mentioned. Since the intrusion of dikes is expected to be under the extensional stress field with maximum extensional axis normal to the wall (NAKAMURA, 1977), and since the stress field during the formation of the cleavage is expected to be compressional with maximum compressional axis being normal to the cleavage plane, the time of the intrusion is expected to be either after the deformation phase of the cleavage formation, or during the deformation phase but at the pause of the compressional stress. In a case of the inclined intrusion from the cleavage structure, the thinner branches of the dike become parallel to the cleavage, or elongate breccias of the country tuff breccia were found to be cut by the dike (Fig. 16). Thus two stages of cleavage formation among the main cleavage structures appear probable; one anterior and the other posterior to the dikes.

3.3.2. The Heritage altered dolerites

Massive and altered dolerite dikes or sills, from tens of meters to about 100 meters thick, some of which are associated with small dikes, from tens of centimeters to several meters thick, are exposed at Soholt Peaks, Edson Hills, High Nunatak, Liberty Hills, and Wilson Nunataks intruding into the rocks of the Heritage Group.

CRADDOCK *et al.* (1964) reported basic sills intruding into the Crashsite Quartzite in the northeastern Heritage Range, and HJELLE *et al.* (1978) considered the gabbro to be of late Paleozoic age, pointing out that their petrochemical character differs from the Jurrasic trap of the Pensacola Mountains. All or part of the basic intrusions mentioned by these authors may be referred to the Heritage altered dolerites, although in the present study, the time of intrusion is considered to be pre-Devonian. The green, clastic country rocks cropping out in the Wilson Nunataks, intruded by one of the Heritage altered dolerites, are referred to the Crashsite Quartzite by CRADDOCK (1969), but are believed to belong to the Heritage Group by HJELLE *et al.* (1978). If the former was the case, the Heritage altered dolerites should have reasonably been considered to be post-Crashsite Quartzite; because this contradicts the isotope age data, HJELLE *et al.* (1978) may be correct in stating that the green clastic rocks of the Wilson Nunataks belong to the Heritage Group.

The dolerites affect recrystallization on the preexistent cleaved rocks, but a faint cleavage structure is developed locally in the dolerite masses (Figs. 17, 18, 19,

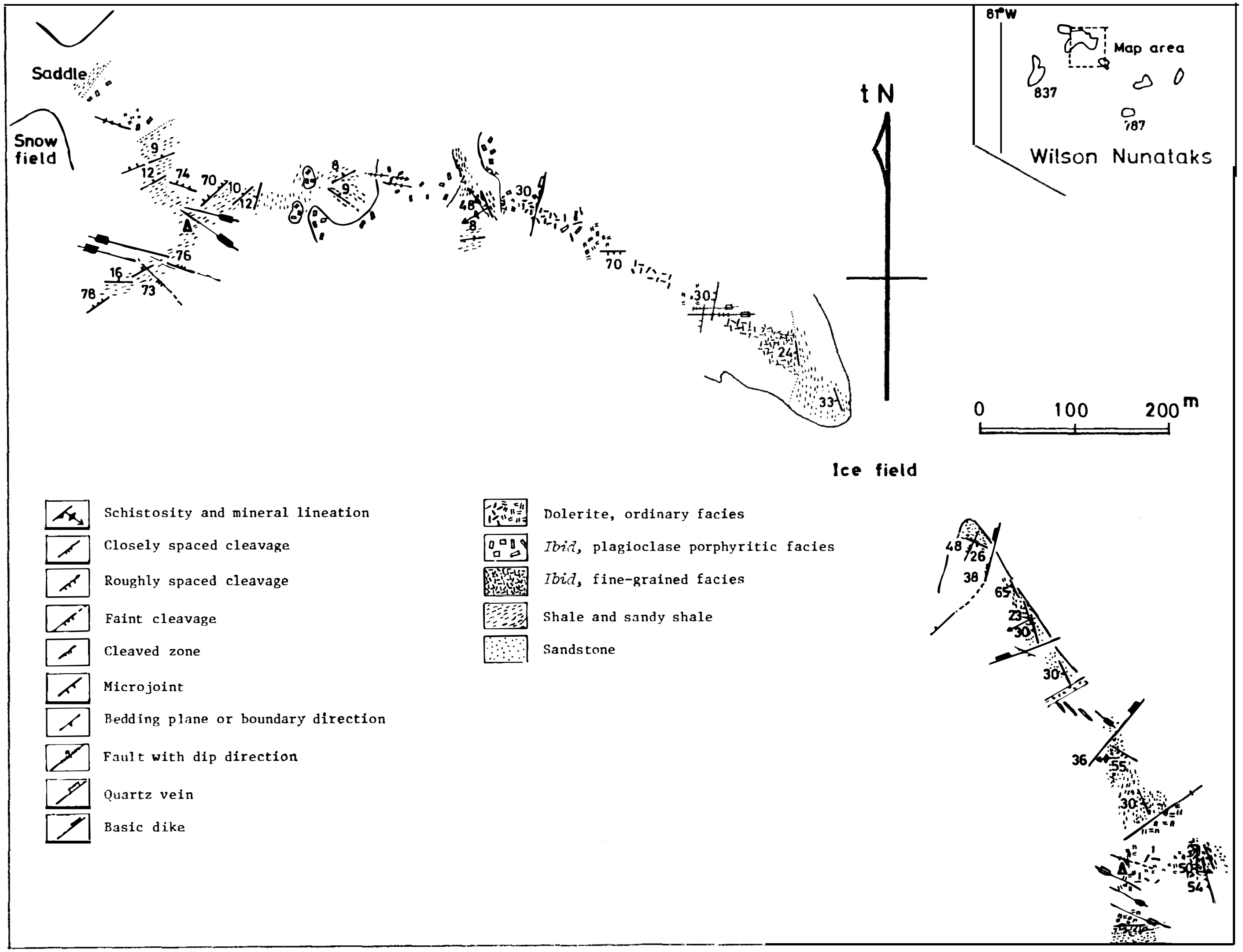


*Fig. 17. Occurrence of the Heritage altered dolerites and newer and older cleavages at the main nunatak of the Wilson Nunataks (for explanation, see text).*

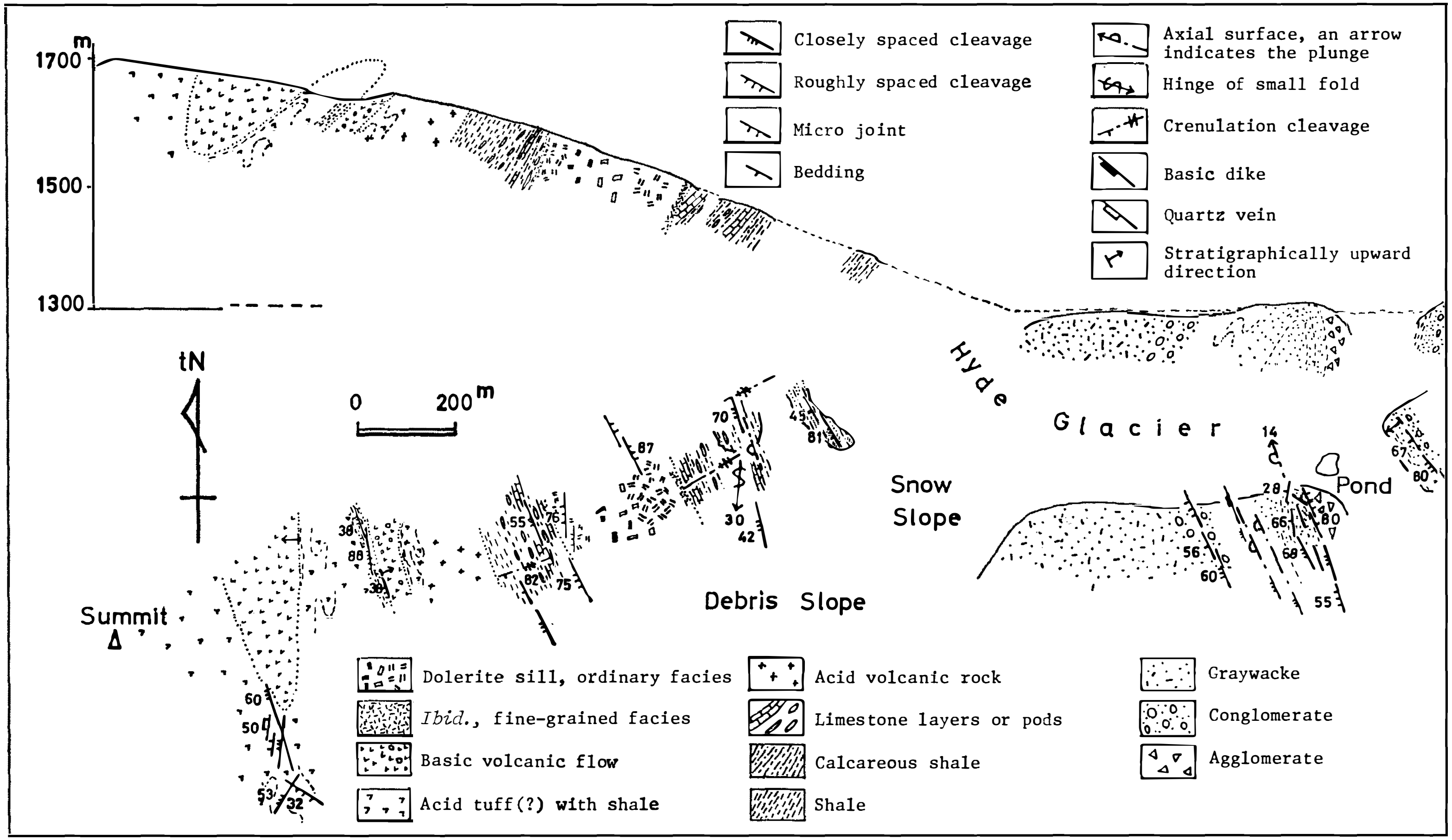


*Fig. 18. Occurrence of the Heritage altered dolerites at the Hyde Glacier, Edson Hills. Only the roughly spaced cleavage develops locally in the dolerite in contrast to the strongly cleaved country rocks.*

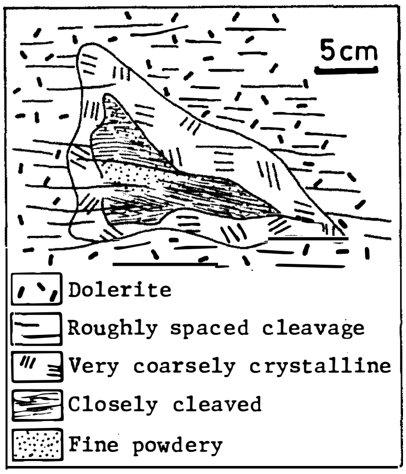


*Fig. 19. Xenolith of a limestone schist with its margin annealed along the contact with the country dolerite. (Point 80010604, at the western margin of the dolerite body in Fig. 18). (cf. Photo 18).*

Photo 18) and in the country rocks, as mentioned earlier in Section 3.2.3. The altered dolerites might have been intruded after the formation of the main cleavage structures of the country rocks of the Heritage Group, but might have predated the formation of the roughly spaced cleavages. The minimum K-Ar ages of about 400 Ma of these rocks indicate that these rocks predate at least a part of, and probably all of, the Crashsite Quartzite. The Ordovician dolerites reported by REX (1972) from western Queen Maud Land to the Shackleton Range may possibly be referred to the Heritage altered dolerites.

### *3.4. Mineral veins*

Mineral veins were found sporadically throughout the survey areas. They are calcite, chlorite-quartz, and epidote-chlorite veins, among which chlorite-quartz veins are important for the interpretation of a metamorphic-tectonic history.

The chlorite-quartz veins are widespread throughout the survey areas, in rocks of the Heritage Group and Crashsite Quartzite, and rarely, in the Heritage altered dolerites. These veins are characterized by their cutting of the main cleavage structures, but sometimes showing some deformation. Quartz is generally equant in shape, but represents distinct deformation lamella or Böhm lamellae or elongate subgrain structures under microscope (Photo 19). Chlorite is characteristically wormy and shows negative elongation throughout the veins from all over the survey areas. Albite, epidote, or calcite are sometimes associated.

In the northwestern area, these veins are associated with the longitudinal kink folds (Fig. 20). In the Edson Hills, the chlorite-quartz veins cut deformed epidote-chlorite veins, the latter being associated with one of the Hyde Glacier cleaved dikes (Fig. 21). Thus the chlorite-quartz veins possibly provide criteria of chronological classification of the main cleavages as the younger cleavage structures either related to the longitudinal kink folds or postdating it, and the older ones cut

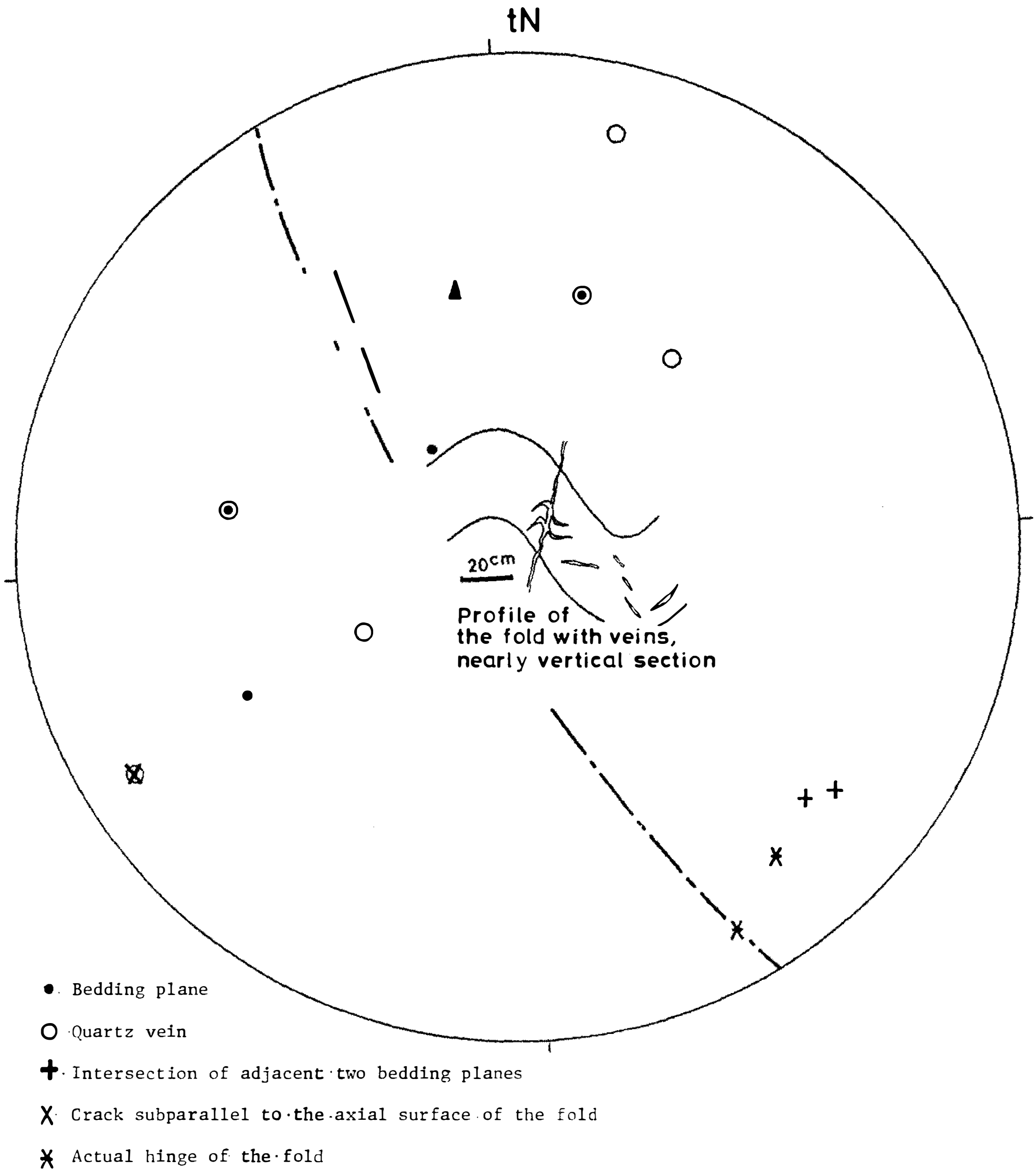


*Fig. 20. Stereographic projection and sketch (nearly vertical section) of the chlorite-quartz vein in association with the longitudinal small kink fold. (Point 79121004C, at the northern end of the Reuther Nunataks, northwestern area of the Heritage Range). A great circle denotes the axial surface of the small kink fold.*

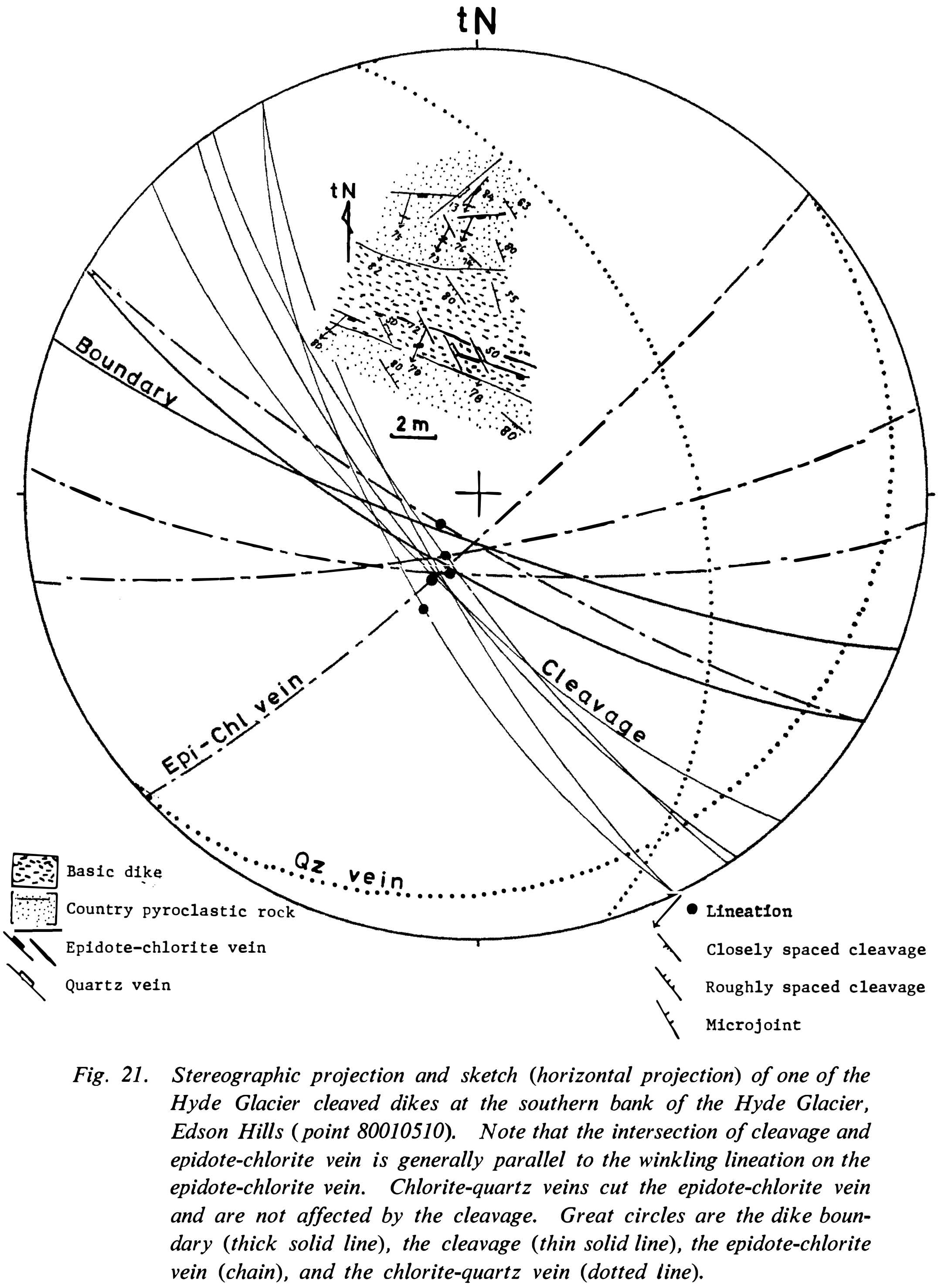


*Fig. 21. Stereographic projection and sketch (horizontal projection) of one of the Hyde Glacier cleaved dikes at the southern bank of the Hyde Glacier, Edson Hills (point 80010510). Note that the intersection of cleavage and epidote-chlorite vein is generally parallel to the winkling lineation on the epidote-chlorite vein. Chlorite-quartz veins cut the epidote-chlorite vein and are not affected by the cleavage. Great circles are the dike boundary (thick solid line), the cleavage (thin solid line), the epidote-chlorite vein (chain), and the chlorite-quartz vein (dotted line).*

by the vein; the older cleavage is that developed in the Hyde Glacier cleaved dikes and the younger one is that associated with the longitudinal kink folds.

From the above discussion and from that given on the Hyde Glacier cleaved dikes, the main cleavage structures are divided into three chronologic groups: pre-Hyde Glacier cleaved dikes, between the Hyde Glacier cleaved dikes and the chlorite-quartz veins, and during or after the chlorite-quartz veins.

*3.5. Outline of metamorphic recrystallizations and its relation to cleavage structures*

The metamorphic recrystallization is complete in some strongly cleaved rocks, but incomplete in many less cleaved rocks. Metamorphic minerals are quartz, albite, calcite, white micas, chlorites, epidote minerals, mica clay minerals, and stilpnomelane, many of them developing parallel to the main cleavage structures (*cf.* Photo 21); thus the main cleavage composed of continuous or closely spaced cleavages are of the slaty cleavage type or schistose in most cases. Basaltic lavas, tuff breccias, and strongly cleaved dikes are also completely altered to the same extent as the surrounding clastic rocks, and actinolite and green biotite develop locally in them. Fragmental muscovite is almost always completely preserved, but biotite is generally completely decomposed to chlorite + leucoxenic matter in cleaved rocks but only partly decomposed in weakly cleaved rocks. Plagioclase is generally completely altered to albite + calcite + sericite or albite + zoisitic mineral aggregate.

The Heritage altered dolerites and associated thin dikes are either completely or partly altered to form actinolite, chlorite, epidote, muscovite, zoisitic mineral, calcite, and albite. The clastic country rocks around the dolerites resemble a hornfelse; many have numerous scattered fine scales of chlorite and/or white mica, and some of them appear to be altered from hornfelsic biotite judging from crystal shape and occurrence. Porphyroblastic chloritoid locally occurs (Photo 20) which is often altered to chlorite completely or incompletely along cracks in some cases, or gradually without a conspicuous boundary with the chloritoid in other cases.

In some psammitic rocks where schistosity-forming sericite and chlorite are developed, or in some doleritic intrusions where chlorite and actinolite are well developed, aggregates of minute grains of mica clay minerals are common; they may indicate a possible superposition of the very low grade metamorphic recrystallization in a later period.

In total, the grade of the metamorphism is assumed to be around the lower temperature portions of the low grade of WINKLER (1974). Metamorphic recrystallization at around this grade is reported to have been detected on all rocks of the Ellsworth Mountains except those of the Polarstar Formation, which is considered to be of the laumontite facies (CRADDOCK *et al.*, 1964; CASTLE and CRADDOCK, 1975; HJELLE *et al.*, 1978). The metamorphic recrystallization, however, might have taken place three or four times. First, schistosity-forming sericite, chlorite, epidote minerals, and albite, associated with the main cleavage formation; second, chlorite (possibly originated from biotite), muscovite, and chloritoid associated with the intrusion of the Heritage altered dolerites; third, chlorite alteration over the thermally recrystalline minerals in rocks around the dolerite intrusions. The quartz-chlorite vein may belong to the third metamorphic recrystallization. Development of the later mica clay minerals may or may not be the fourth metamorphic recrystallization. In detail, however, superposition of schistosity and closely spaced cleavage structure, both being associated mainly with sericite and chlorite recrystallization, are common (Photo 21). Consequently, the first metamorphic recrystallization may possibly be divided further. Detailed microstructural study is needed.

### *3.6. K-Ar dating*

Seven specimens have been dated by the K-Ar whole rock method by Teledyne Co., N.J., United States; the results are presented in Table 1. There are some problems in applying the K-Ar dating method on such altered and polymetamorphic rocks as were found in the present study. However, the author prefers tentatively to consider these K-Ar dates to indicate the age when the rock has come to be a

*Table 1. K-Ar dating of rocks from the Heritage Range.*

| Specimen No. | Analyzed material | %K | scc $Ar^{40Rad}$/g×$10^{-5}$ | % $Ar^{40Rad}$ | Isotope age | Petrography and locality |
|---|---|---|---|---|---|---|
| MY80010602 | Whole rock | 0.43 | 0.737 | 87.8 | 396±20 | Weakly altered dolerite about |
| | | 0.43 | 0.742 | 84.9 | | 200 meters, thick, Edson Hills |
| MY80010707 | Whole rock | 3.31 | 3.86 | 96.9 | 278±14 | Chlorite-muscovite phyllite, |
| | | 3.34 | 3.92 | 96.0 | | Edson Hills |
| MY69123033 | Whole rock | 0.78 | 1.29 | 91.3 | 381±19 | Altered massive dolerite |
| | | 0.79 | 1.30 | 90.2 | | about 120 meters thick, |
| | | | | | | Wilson Nunataks |
| MY80010801A | Whole rock | 4.85 | 4.75 | 97.8 | 237±12 | Strongly cleaved and altered |
| | | 4.91 | 4.86 | 97.4 | | andesitic dike, Edson Hills |
| MY80010801B | Whole rock | 2.35 | 2.49 | 96.6 | 254±13 | Cleaved and altered basaltic |
| | | 2.35 | 2.50 | 96.2 | | dike, Edson Hills |
| MY79120701 | Whole rock | 2.53 | 3.29 | 97.5 | 308±15 | Muscovite-chlorite phyllite, |
| | | 2.55 | 3.34 | 96.0 | | Fraser Ridge |
| MY79122909B | Whole rock | 0.23 | 1.07 | 89.7 | 935±47 | Fine-grained chlorite-musco- |
| | | 0.23 | 1.12 | 90.0 | | vite-quartz-feldspar rock(me- |
| | | | | | | ta-pelite), Wilson Nunataks |

Analyzed by the Teledyne Isotopes Co., N.J., U.S.A., with the following constants: $\lambda_{\beta}=4.962\times10^{-10}$ $a^{-1}$, $\lambda_{\varepsilon}=0.581\times10^{-10}$ $a^{-1}$, $K^{40}=1.167\times10^{-4}$ atom per atom of natural potassium.

closed system with regard to K and Ar; in case of incompletely recrystallized polymetamorphic lower grade rocks, however, the obtained age may often be a mixture of the superposed geologic events.

The 935 Ma age of the fine-grained green rock from the Wilson Nunataks, occurring very near to the intrusive rocks of the Heritage altered dolerites is problematic; but if we have the standpoint as mentioned above, this rock is assumed to be the basement metasediments drawn upward by the upheaval of the dolerite, and the age may be the mixture of the metamorphism of the basement (of the Nimrod Orogeny?) and the newer metamorphism.

The 381 and 396 Ma ages of the Heritage altered dolerites may be the mixture age of the intrusion and the later metamorphisms; *i.e.* may provide the minimum age of the intrusion.

The 278 and 308 Ma ages of somewhat compact schistose rocks may be mixture ages of the first to the fourth metamorphic recrystallizations, but most likely may be reflections of the cooling at around this age caused by the uplift and denudation of the regional scale or some metamorphic and tectonic events before or during the Whiteout Conglomerate, thus providing the cooling age or the minimum age of the metamorphic and tectonic events. CRADDOCK (1970) gave a 304 Ma K-Ar whole rock age from the southern part of the Heritage Range, which may also be from this group of ages.

The 237 and 254 Ma ages of cleaved basic dikes may be the mixture ages of the later metamorphic recrystallizations but most likely the maximum age of the time of formation of roughly spaced cleavage and the fourth metamorphic recrystallization.

Although isochron age dating is needed to obtain somewhat more accurate data, especially on the igneous rocks, the present K-Ar dates provide valuable chronological data on the geologic history of the Ellsworth Mountains.

## 4. Discussions

(1) The criterion for the analysis of geologic history

In the present discussion, the writer wishes to stress the superposition of the deformations and its possible bearing on the polyorogenic interpretation of the Ellsworth Mountains.

There are too many variables represented in the geologic events discussed in the earlier sections. For example, in the discussion on the main cleavages, several possibilities of determining several kinds of cleavages of differing origin were suggested. In order to clean up some of the complexities of data, some of which may include both significant but also unimportant geologic information, the writer prefers to use subjective geologic criteria as a basis for the following discussions of the structural history of the Ellsworth Mountains. The Heritage altered dolerites are the major criteria for this discussion.

(2) Geologic events before and after the Heritage altered dolerites

A distinctive gap lies before and after the Heritage altered dolerites. Geologic events predating the dolerites are the accumulation of the Heritage Group, formation of most part or some part of the main cleavages, formation of most part or some part of the longitudinal close folds, and first metamorphic recrystallization. Geologic events postdating the Heritage altered dolerites are the accumulation of the Crashsite Quartzite and the younger formations, formation of the roughly spaced cleavages, part of the main cleavages, part of the longitudinal close folds, longitudinal open folds, and the second, third, and fourth metamorphic recrystallizations. Accumulation of the Crashsite Quartzite is problematic only from the field evidence, but is considered to be later than the dolerites, as mentioned below.

The 381 and 396 Ma K-Ar ages of the Heritage altered dolerites are conformable to the above discussion. These ages may be minimum ages of the intrusion of the Heritage altered dolerites, rejuvenized only slightly by the later metamorphism. The degree of the rejuvenization was far smaller than the cleaved metamorphic rocks because the dolerites show very poor cleavage, and consequently, weak recrystallization only locally.

These considerations indicate the time of the intrusion of the Heritage altered dolerites to be pre-Devonian. Since the volcanigenic material is completely lacking in the lower part of the Crashsite Quartzite (CRADDOCK *et al*., 1964; CRADDOCK, 1969; HJELLE *et al*., 1978), the Heritage altered dolerites almost certainly predate the Crashsite Quartzite.

(3) Chronological classifications either among the longitudinal close folds or among the main cleavages

Resolution of the great tectonic and metamorphic gap at the time just before the Heritage altered dolerites supports the possibilities of further divisions of the main cleavages or the longitudinal close folds into at least two cleavages or folds; these possibilities were already mentioned in Sections 3.2, 3.3 and 3.4.

One possibility is the division of the longitudinal close folds into the older longitudinal close fold mainly observed in the southern area and the younger longitudinal kink fold developed in the northwestern area. One reason for the possibility is that the closely spaced cleavage does not generally develop over the Heritage altered dolerites in contrast to the country rocks which are generally strongly cleaved. Another reason is that the longitudinal kink fold and the associated chlorite-quartz vein develop not only over the rocks of the Heritage Group but also over the rocks of the Crashsite Quartzite, which is later than the Heritage altered dolerite. Therefore, the main cleavages before the Heritage altered dolerites are considered to be associated with the longitudinal close folds excepting the longitudinal kink fold; the latter fold might have associated axial plane cleavage structures only locally.

Another possibility is the postposition of all the longitudinal close folds after the Crashsite Quartzite and consequently, the main cleavage should be chronologically divided at least into two groups as one predating the Heritage altered dolerites and the other postdating it; the former might have been associated with some earlier tectonism such as the inclined folds, and the latter, with the longitudinal close folds including the longitudinal kink folds. The rigid property of the altered dolerite mass might have resulted in the poor development of the lately formed portions of the main cleavages. If we are to prefer the latter possibility mentioned above, part of the main cleavage being expected to be later than the Heritage altered dolerite might have been inhomogeneous, and most of the main cleavage might belong to the pre-Heritage altered dolerite events, judging from occurrences of the dolerites and the cleavages at the Wilson Nunataks as mentioned in Section 3.3.2.

(4) The geologic events after the Crashsite Quartzite

Some tectonic and metamorphic events after the Crashsite Quartzite are expected to have taken place as already mentioned: the longitudinal kink fold and associated cleavage as parts of the main cleavages, longitudinal open folds and associated roughly spaced cleavages, and probably the third and fourth metamorphic recrystallizations.

HJELLE *et al.* (1982) stated that the intensity and style of folds differ significantly between the Crashsite Quartzite and the Whiteout Conglomerate, and insisted that there may be a stratigraphic-tectonic gap at the base of the Whiteout Conglomerate. They further mentioned that rocks lower than the Polarstar Formation belong to the similar greenschist facies metamorphic conditions, and a gap in metamorphic conditions exists between the lower formations and the overlying Polarstar Formation, the latter having been reported to belong to the laumontite facies (CASTLE and CRADDOCK, 1975).

It is possible to infer that the longitudinal close folds or the longitudinal kink folds affected strata below the Whiteout Conglomerate, the third metamorphic recrystallization affected the strata below the Polarstar Formation, and the longitudinal open folds and fourth metamorphic recrystallization affected all strata including the Polarstar Formation.

(5) Possibility of chronological division of the main cleavages of pre-Heritage altered dolerites

There is a possibility that the main cleavages formed before the Heritage altered dolerites may be chronologically divided into two, as already postulated in Section 3.3.1 and further discussed in 4(3); one, predating the Hyde Glacier cleaved dikes, this cleavage being expected to have worked as a path for the intrusion, and the other, postdating the Hyde Glacier Conglomerate, resulting in the formation of the cleavage structure of both the cleaved dikes and the conglomerate. The superposition of closely spaced cleavages over the continuous cleavages found sporadically in the southern areas, as already mentioned in Section 3.5, may reinforce the possibility.

(6) Problems of the ?Precambrian Minaret Group

The possibility of the Minaret Group as Precambrian (?) (CRADDOCK, 1969), composed mainly of the limestone formation cropping out at the Marble Hills, appears to be improbable as already mentioned in Section 3.1.1. If we attempt to identify any formations as older than the Heritage Group, some conglomerate formations of the present Heritage Group cropping out in the Liberty Hills, Edson Hills, and Independence Hills should be considered because of the stratigraphy (*cf.* Figs. 2a, b), and the Heritage Group should be restricted to its upper part. If this consideration is accepted, the unconformable relationship at the base of the upper part of the Heritage Group (the restricted Heritage Group) is also possible where the Hyde Glacier Conglomerate is believed to constitute the basal part of the restricted Heritage Group; the lower part of the Heritage Group overlain by the Hyde Glacier Conglomerate is of possible ?Precambrian age.

Some green rocks cropping out at the main nunatak of the Wilson Nunataks may also be older than the Heritage Group because of the older K-Ar age (see Table 1).

(7) Polyorogenic interpretation of the recurrent geologic events of the Ellsworth Mountains and its implication to other areas of Antarctica

Various geologic phenomena and their timing described in the foregoing pages can be summarized as in Fig. 22. Thus four or more metamorphic-tectonic events appear to have operated in the Ellsworth Mountains, although the figure includes some uncertain differentiations of the older geologic phenomena which are mentioned previously. Thus a polyorogenic interpretation of the Ellsworth Mountains geology is obtained. Figure 23 shows a tentative geologic history of the Ellsworth Mountains which will be discussed in the followings.

Metamorphic and tectonic events following deposition of the Polarstar Formation, as shown by the fourth metamorphic recrystallization, and probably the longitudinal open fold are possibly reflected by the maximum K-Ar ages of 237 and 254 Ma. These events coincide well with the early Mesozoic Ellsworth Orogeny of CRADDOCK (1972), or the Weddell Orogeny of FORD (1972) recognized in the Weddell Sea area.

Metamorphic and tectonic events following deposition of the Crashsite Quartzite, and probably before or during deposition of the Whiteout Conglomerate as suggested by HJELLE *et al.* (1982) may be reflected by the minimum K-Ar ages of 278 to 308 Ma. A K-Ar age of 297 Ma of a dolerite from the Shackleton Range (REX, 1972; CLARKSON, 1982) might possibly be referred to this event. Ages of these events are conformable with the Borchgrevink Orogeny developed in northern Victoria Land and in West Antarctica (CRADDOCK, 1972; ELLIOT, 1975), although ADAMS *et al.* (1982a) and BRADSHAW *et al.* (1982) lately revised the age of the Borchgrevink Orogeny as being much older, around 400–420 Ma, and

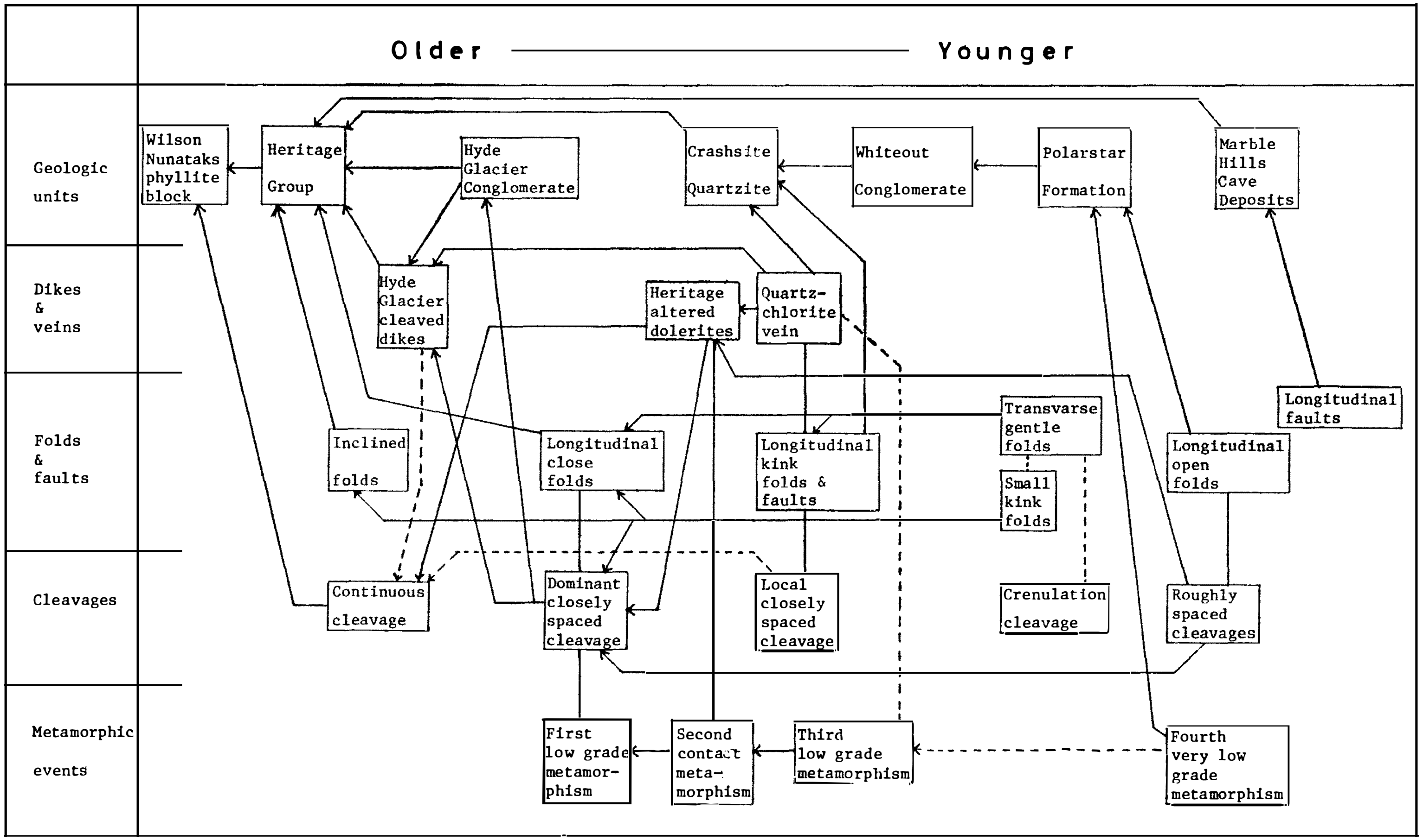


*Fig. 22. Timing among observed geologic phenomena. Tie lines with arrows indicate either definit (solid-line) or probable (dashed line) time relationships; the head is older. Tied phenomena without an arrow are simultaneous.*

| Stratigraphy | | Dikes and veins | Folds | Cleavages | Metamorphism | K-Ar ages (Ma) | Correlation with other areas |
|---|---|---|---|---|---|---|---|
| | ? | | Longitudinal open folds | Roughly spaced cleavages | 4th meta. (very low grade) | 235 - | Ellsworth Orogeny |
| Permian | Polarstar Formation | | Transverse gentle folds ↓ ? | Crenulation Cleavages ↓ ? | | | |
| | ? | | | | | | |
| Permo-Carboniferous | Whiteout Conglomerate | | | | | | |
| | ? | Quartz-chlorite vein | Longitudinal kink folds ↑ | Local closely spaced cleavage | 3rd meta. (low grade) | 300 ± | Late Borchgrevink Orogeny |
| Devonian & (?) pre-Devonian | Crashsite Quartzite | | | | | | |
| | ? | Heritage altered dolerites | | | 2nd meta. (low grade contact) | 396 + | |
| | | | Longitudinal close folds ↑ | Dominant closely spaced cleavage ↑ | 1st meta. (low grade) | | Early Borchgrevink or Ross Orogeny |
| | ? ↑ Hyde Gl. Conglomerate | Hyde Gl. cleaved dikes | | | | | |
| | ? | | Inclined fold | Continuous cleavage ↓ | (?)Earlier meta. | | Ross or Beardmore Orogeny |
| Cambrian | Heritage Group ↑ | | | | | | |
| | ↓ ? | | | | | | |
| (?)Precambrian | Wilson Nunataks phillite block | | | | | (?)935 | (?)Nimrod Orogeny |

*Fig. 23. Tentative geologic history of the Ellsworth Mountains. Arrows indicate probability of the shift of all (solid line) or a part (dashed line) of the events. Question marks indicate uncertainty as to either the situation (time) or the existence of the concerned phenomena.*

distinguished the 300–380 Ma ages as related to the Admiralty intrusives. It may be noted that ADAMS *et al.* (1982b) reported *ca.* 400 Ma K-Ar ages on phyllite from the central Transantarctic Mountains, and considered the ages to reflect uplift and cooling of the area.

Metamorphic and tectonic events after deposition of the Heritage Group and before the intrusion of the Heritage altered dolerites may be referred to the K-Ar minimum ages of 381 and 396 Ma. These events may be referred to either the restricted (BRADSHAW *et al.*, 1982) Borchgrevink or the circumscribed (LAIRD and BRADSHAW, 1982) Ross Orogenies, the latter being widespread throughout the Transantarctic Mountains as having ages of *ca.* 500 Ma. If the Heritage altered dolerites are referred to the dolerites of *ca.* 450 Ma ages reported from western Queen Maud Land to the Shackleton Range (REX, 1972), as mentioned in Section 3.3.2, these events are more probably referred to the Ross Orogeny, and the 381 and 396 Ma ages may be reflections of upheaval and cooling. HJELLE *et al.* (1982) pointed out the lithologic inhomogeneity among rocks of the Dunbar Ridge Formation and suggested a major disconformity at the base of the Crashsite Quartzite. It is possible that the events interpreted by HJELLE *et al.* (1982) correspond to the metamorphic-tectonic events mentioned above.

Possible metamorphic and tectonic events before the Hyde Glacier Conglomerate may be referred to either the Ross or the Beardmore Orogenies; this observation, however, should be examined further from the stratigraphic studies.

Data on the geologic history of the Weddell Sea margins and of related areas in Antarctica are becoming more abundant (*e.g.*, BRADSHAW *et al.*, 1982; ADAMS *et al.*, 1982b; CLARKSON, 1982; SCHMIDT and FORD, 1969) since the early 1970's when a relatively simple orogenic history was explained (*e.g.*, CRADDOCK, 1972). A more complicated polyorogenic history of the Ellsworth Mountains can now be explained on the basis of detailed geologic studies of nearby areas. There are two contrasting viewpoints as to the geologic history of the Ellsworth Mountains; either the mountains had been located earlier at the eastern margin of the Weddell Sea in alignment with the other ranges of the Transantarctic Mountains (SCHOPF, 1969; CLARKSON and BROOK, 1977), or nearly its present location (CRADDOCK, 1972; FORD, 1972; GRIKUROV *et al.*, 1980). It should be noted that WATTS and BRAMALL (1980), through paleomagnetic analyses, favor a 90° offset of the Ellsworth Mountains after early Ordovician time; the result is advantageous to SCHOPF's suggestion.

Through the present study, the Paleozoic Borchgrevink Orogeny is believed to have affected the Ellsworth Mountains, which places the Ellsworth Mountains on the eastern to northern side of the zone of the Ross Orogeny (CRADDOCK, 1972). But results of recent detailed investigations in northern Victoria Land (BRADSHAW *et al.*, 1982) and Transantarctic Mountains (ADAMS *et al.*, 1982b) suggest that these orogenic zones do not develop with a monotonous polarity in both time and place but are complexly superposed.

Thus the geologic history of the Ellsworth Mountains cannot provide the sole criteria for the earlier location of the mountains. Further detailed analysis on the nature of tectonics of each stage may provide useful data for the study of tectonic evolution of the Weddell Sea margins.

## 5. Conclusion

Preliminary analyses of field data and rock specimens of mainly the Heritage Range have shown several metamorphic-tectonic events ranging from pre-Devonian to early Mesozoic, as follows:

(1) A number of events occurred prior to the intrusion of the Heritage altered dolerites of about 400 Ma or older, including sedimentation of the Heritage Group and probably the Hyde Glacier Conglomerate, intrusion of the Hyde Glacier cleaved dikes, reclined and inclined plunging isoclinal folds, longitudinal close folds (except for the kink folds), formation of continuous cleavages, and low grade (of WINKLER, 1974) metamorphic recrystallization. The closely spaced cleavages might have taken place during these events.

(2) Tectonic and metamorphic events following the intrusion of the Heritage altered dolerites include the sedimentation of the Crashsite Quartzite and younger formations, longitudinal kink folds associated with, in part, the closely spaced cleavages, longitudinal open folds associated with roughly spaced cleavages, and low grade and very low grade metamorphic recrystallizations. Transverse gentle folds, possibly associated with crenulation cleavages, might have taken place during these events.

These two major events may be further divided chronologically, and some probabilities are discussed along with whole rock K-Ar dating and research results of others. A probable succession of tectonic-metamorphic events resulting in the polyorogenic history of the Ellsworth Mountains is as follows, from oldest to youngest:

a) Both of the 935 Ma K-Ar age events and the tectonic and metamorphic events earlier than the deposition of the upper part of the Heritage Group are very problematic and should be examined further. Reference of the latter to the Beardmore or Ross Orogenies has been made, along with problems of further stratigraphic division of the Heritage Group into both (?) Precambrian and Cambrian formations.

b) Tectonic and metamorphic events following the Heritage Group and before the Heritage altered dolerites of older than 396 Ma are distinctive as mentioned above and may be referred to the revised Borchgrevink Orogeny (BRADSHAW *et al.*, 1982) recognized in northern Victoria Land, or more probably, the circumscribed Ross Orogeny found throughout the Transantarctic Mountains (LAIRD and BRADSHAW, 1982).

c) Tectonic and metamorphic events following the Crashsite Quartzite and before or during the Whiteout Conglomerate are low grade metamorphic recrystallization and possibly the longitudinal kink folds associated partly with the closely spaced cleavages. These events are believed to reflect the K-Ar ages around 300 Ma and may be referred to the late Borchgrevink Orogeny, similar ages having been reported from northern Victoria Land, West Antarctica, and in the eastern parts of the Transantarctic Mountains to western Queen Maud Land.

d) Tectonic and metamorphic events following the Polarstar Formation are the very low grade metamorphic recrystallization. Roughly spaced cleavages, longitudinal open folds, and transverse gentle folds observed in the Heritage Range are tentatively included in these events. The maximum K-Ar age of 235 Ma may reflect these events, which may be referred to the Ellsworth Orogeny of CRADDOCK (1972) or the Weddell Orogeny of FORD (1972), recognized in the area around the Weddell Sea.

The polyorogenic history of the Ellsworth Mountains appears evident from the present study. However, the earlier location of the crust of the Ellsworth Mountains and its change during the Paleozoic Era are difficult to resolve from present information. Various kinds of geologic studies, including detailed tectonics, are required for a complete and acceptable analysis.

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*Photo 1. Occurrence of the Hyde Glacier Conglomerate, viewed at the northern slope of the 1447 meter peak, Edson Hills (cf. Fig. 3).*

*Photo 2. Occurrence of the Hyde Glacier Conglomerate at the southern bank of the Hyde Glacier (cf. Fig. 4).*

*Photo 3. Unconformably overlying conglomerate body at High Nunatak (cf. Fig. 6).*

*Photo 4. The Hyde Glacier Conglomerate at High Nunatak (about 120 meters west from the summit) (cf. Fig. 6).*

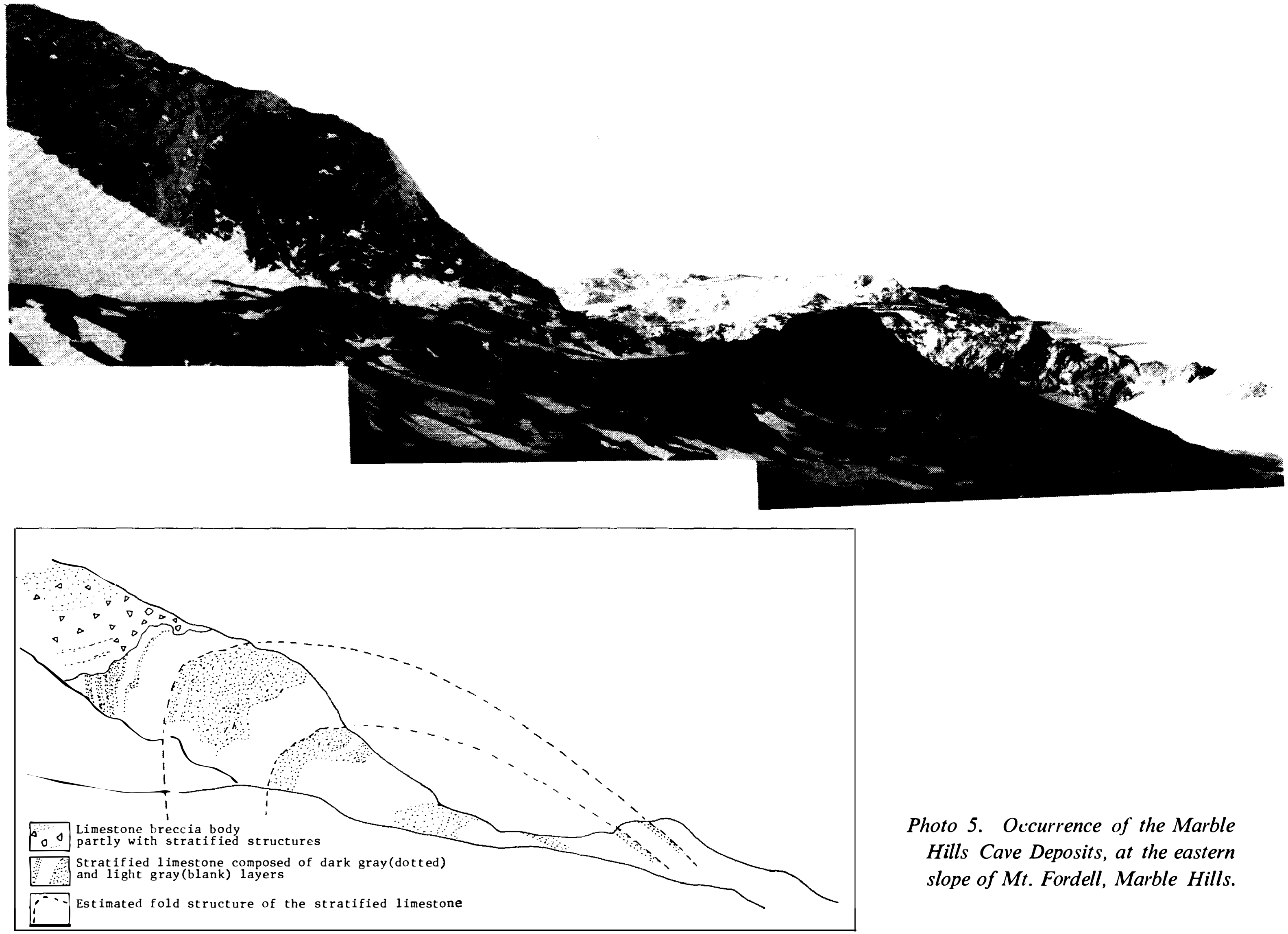


*Photo 5. Occurrence of the Marble Hills Cave Deposits, at the eastern slope of Mt. Fordell, Marble Hills.*

*Photo 6. Marble Hills Cave Deposits, at the "Fold Cliff" of the Marble Hills.*

*Photo 7. Reclined synform at the Marble Hills (cf. Fig. 9).*

*Photo 8. Continuous development of longitudinal close fold at the "Fold Cliff", Marble Hills.*

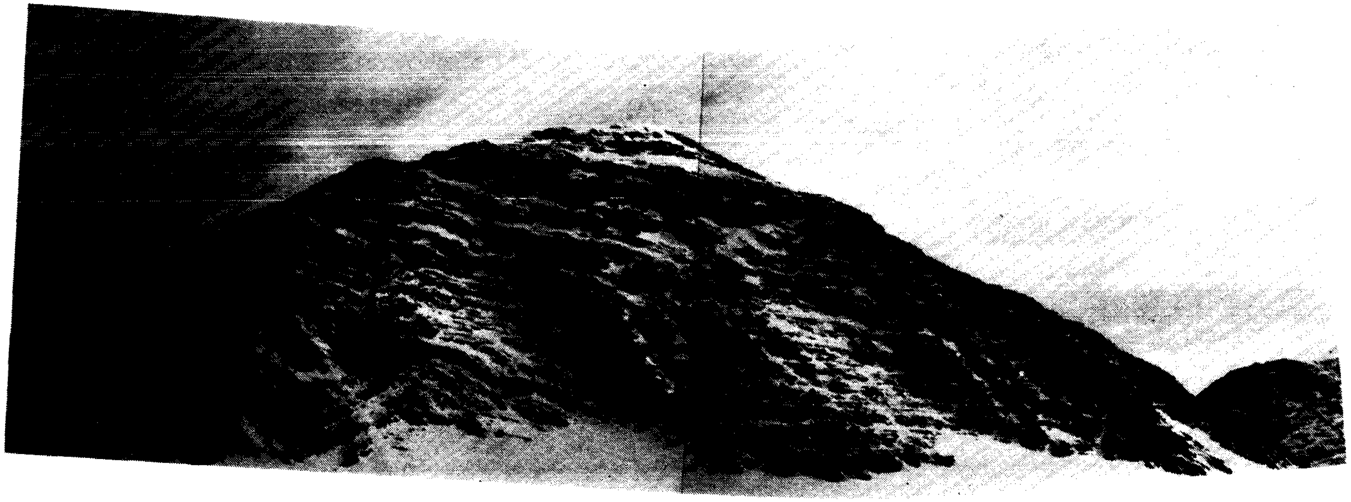

*Photo 9. Longitudinal kink fold at the eastern slope of the Frazier Ridge, northwestern area (cf. Fig. 11).*

*Photo 10. Closely spaced cleavage and transverse shear fractures indicating conjugate sets (Siefker Ridge, northwestern area).*

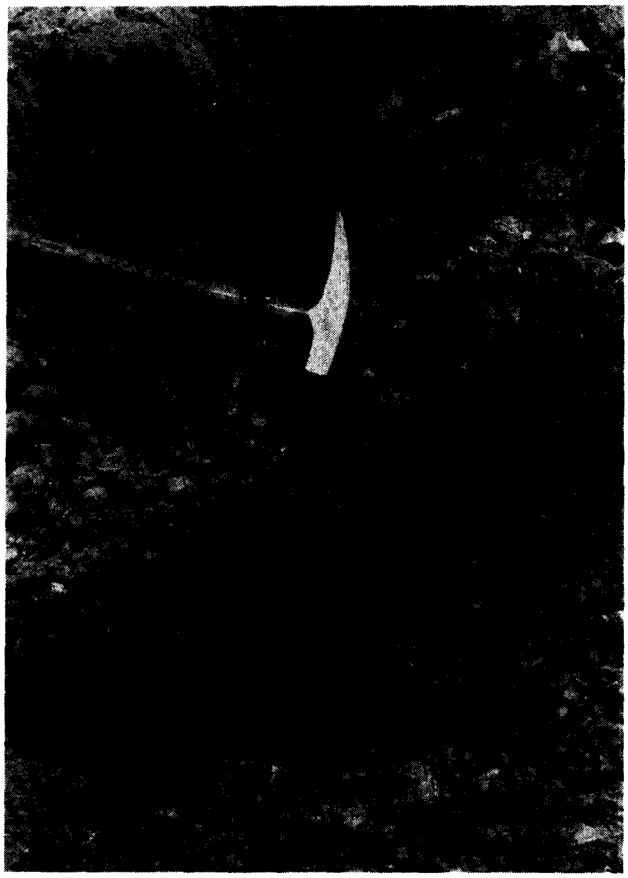

*Photo 11. Transverse small shear fractures on pebbles of the conglomerate of the Heritage Group, at Liberty Hills.*

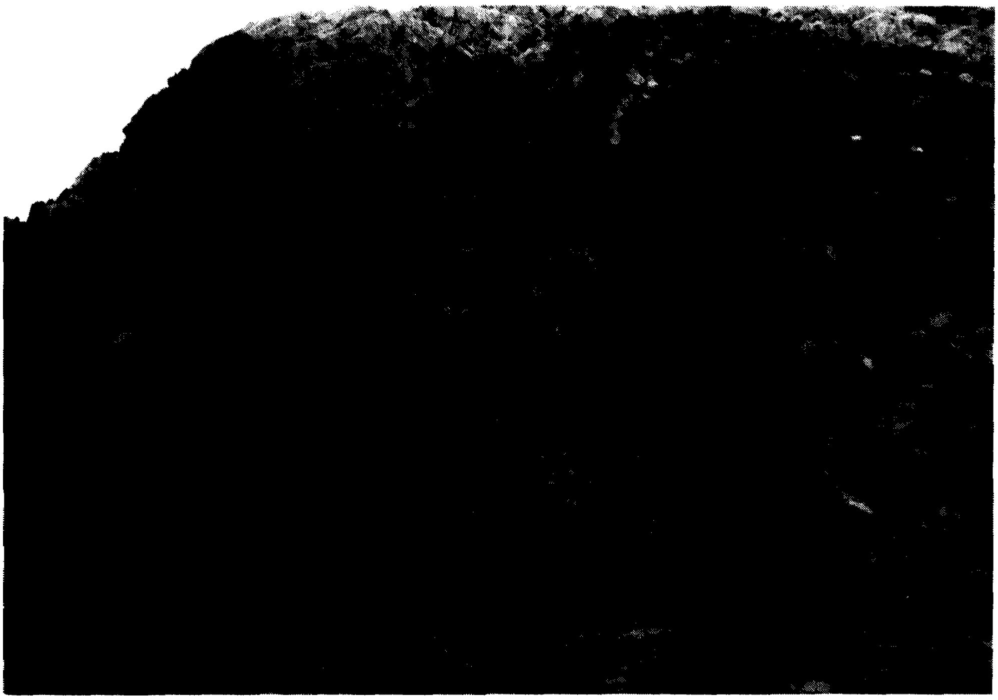

*Photo 12. Longitudinal open fold at the Wilson Nunataks (cf. Fig. 12).*

*Photo 13. Continuous chevron folds in the northwestern slope of Polarstar Peak.*

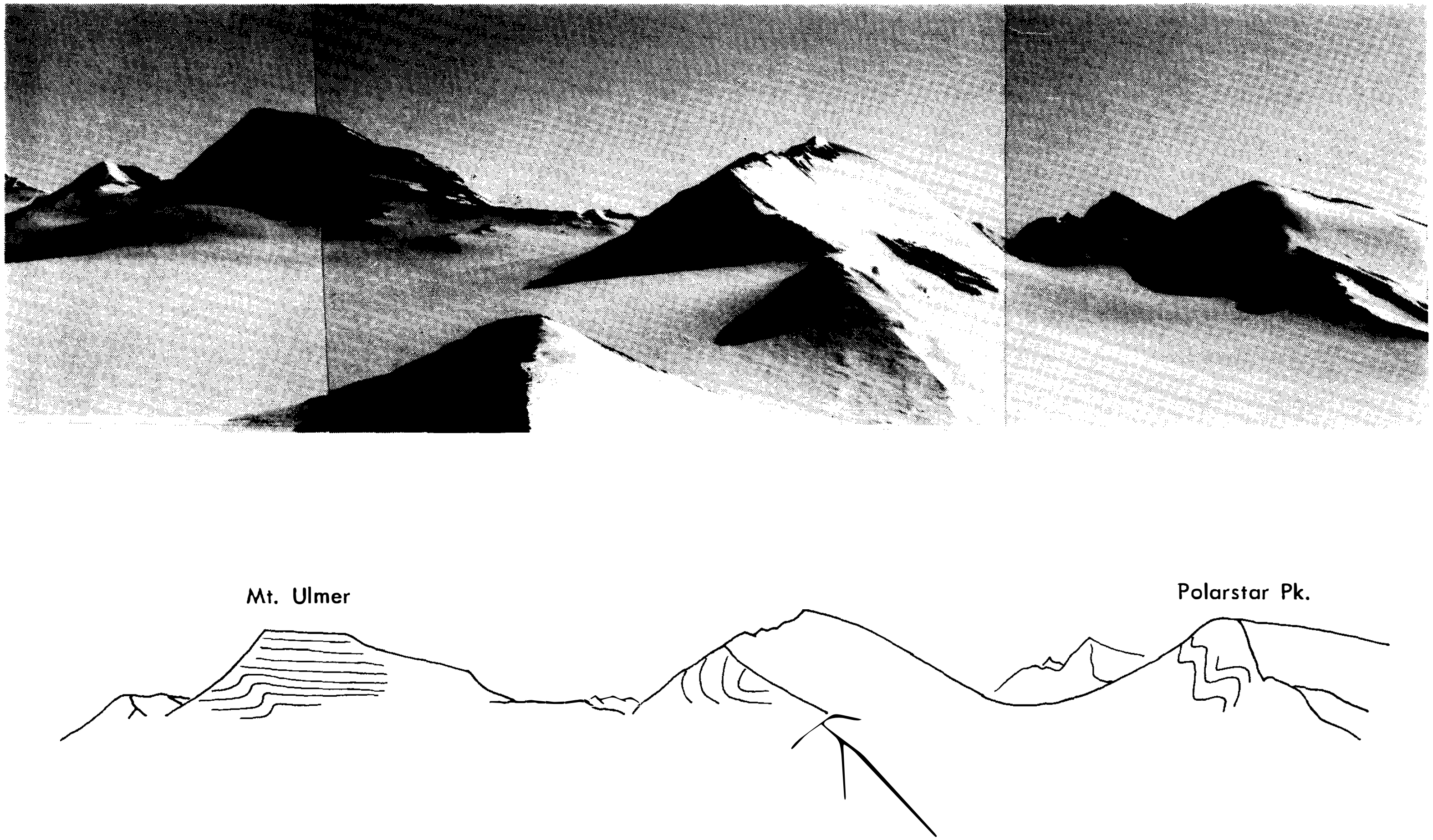


*Photo 14. Discontinuous folds in the eastern slope of Mt. Ulmer–Polarstar Peak area.*

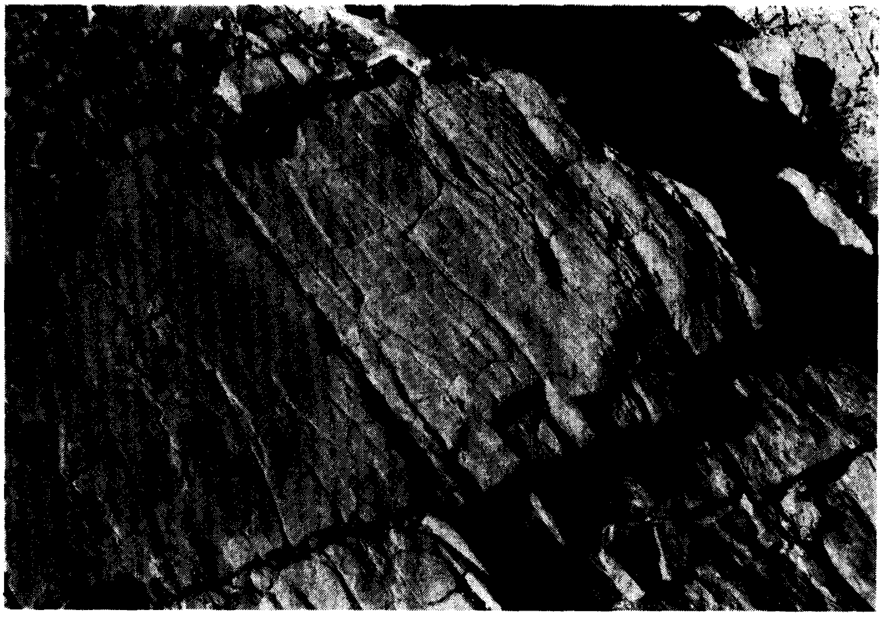

*Photo 15. Weak cleavage structure of the shale, east of Polarstar Peak.*

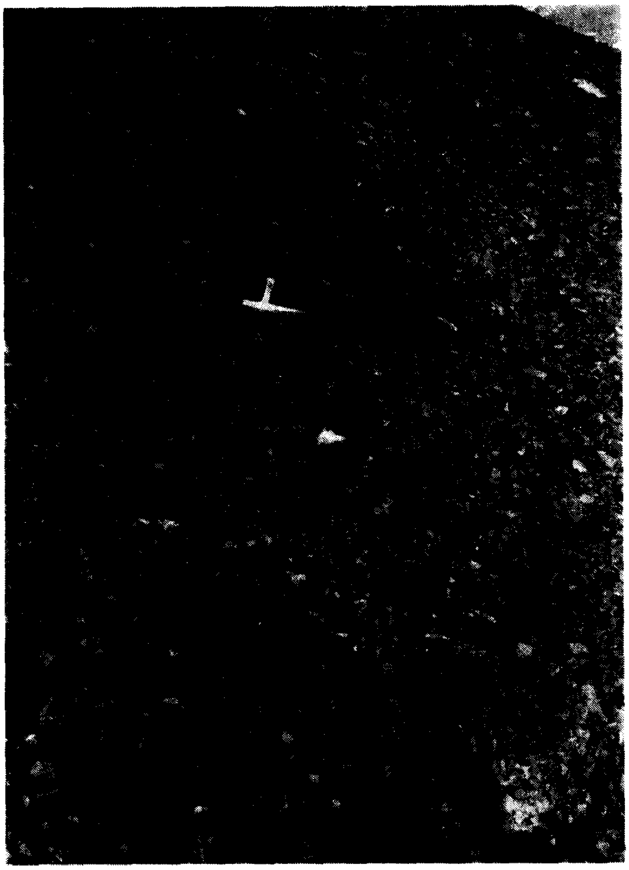

*Photo 16. Transverse small gentle fold at Webers Peaks (cf. Fig. 15).*

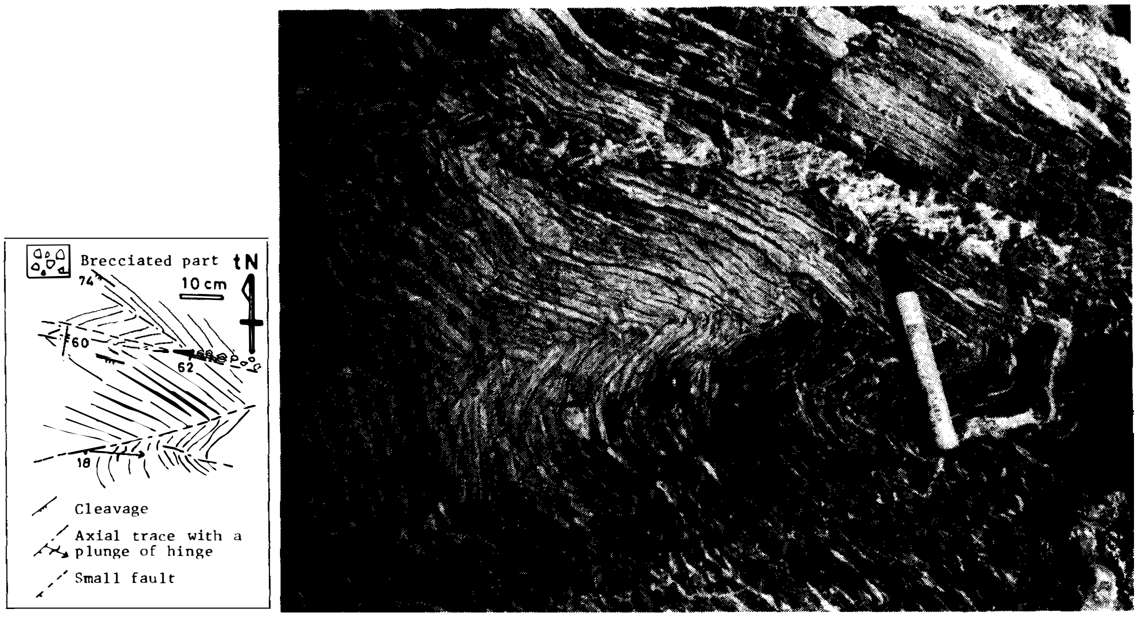


*Photo 17. Small kink fold at the Marble Hills.*

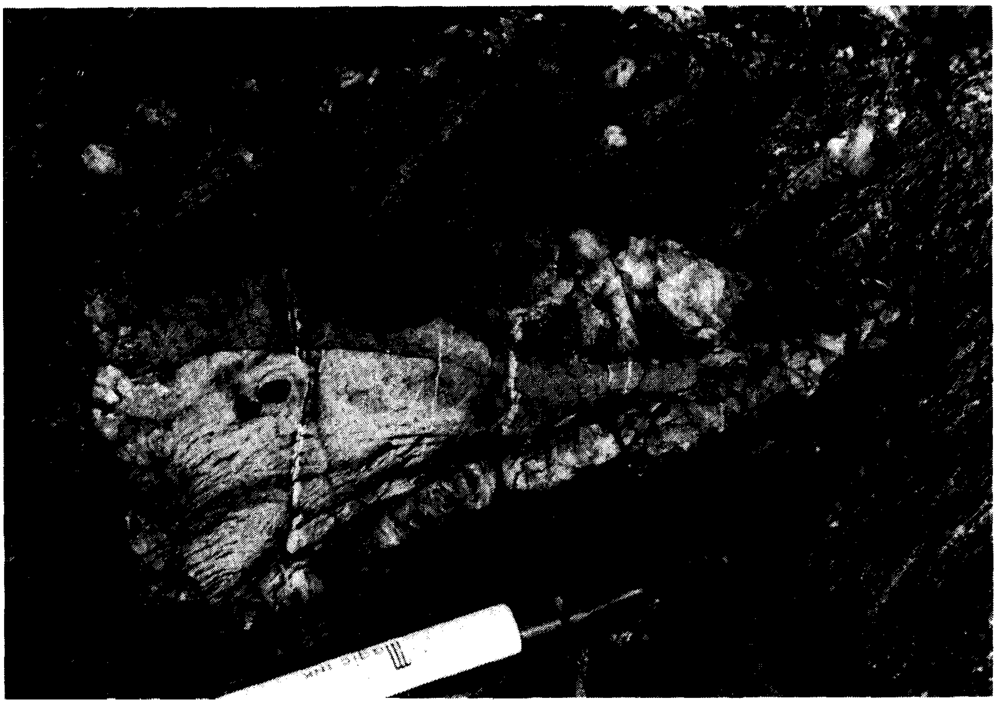

*Photo 18. Xenolithic limestone schist in the dolerite mass at Edson Hills. The margin of the xenolith is coarsely recrystallized (cf. Fig. 19).*

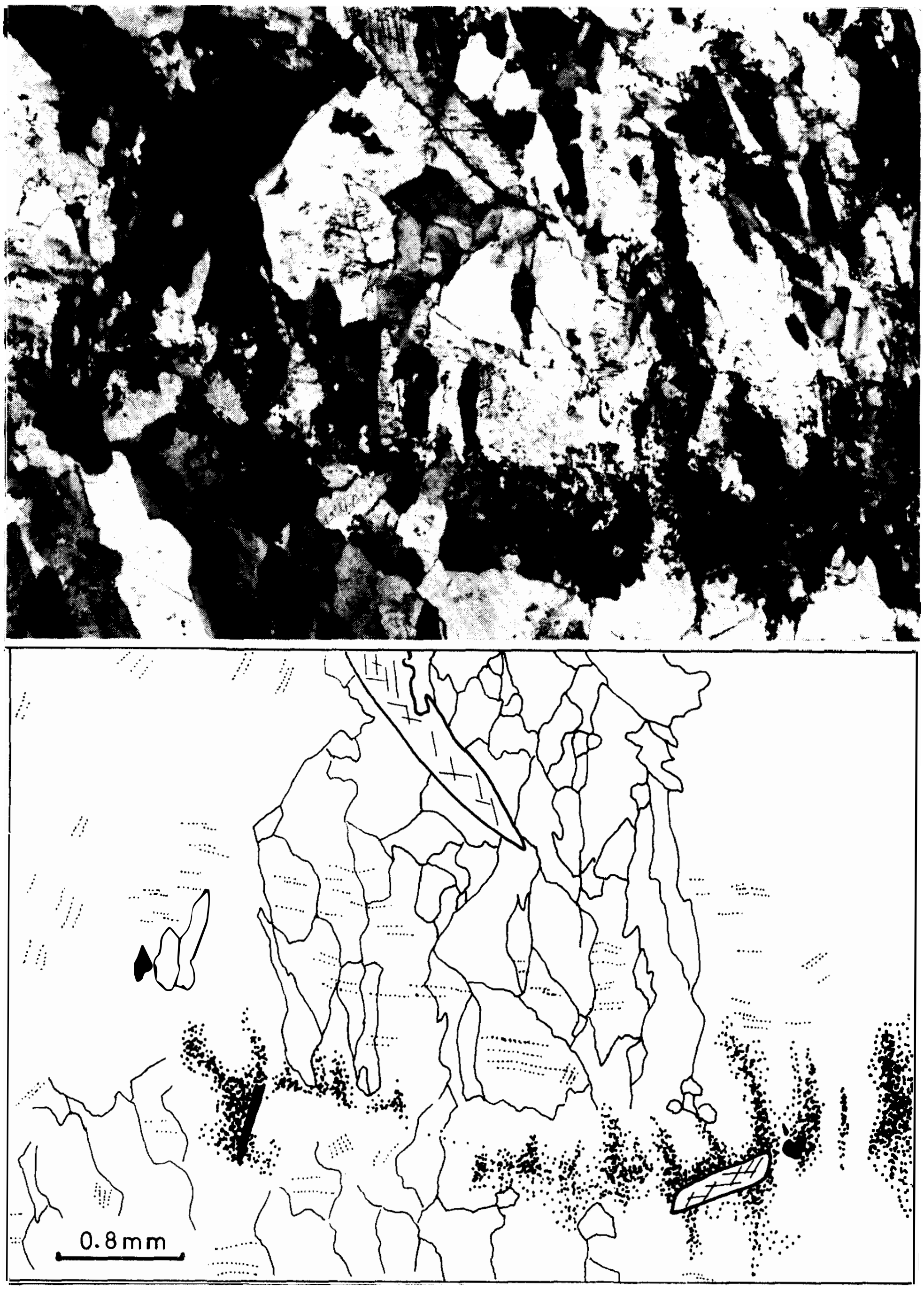


*Photo 19. Photomicrograph of a chlorite-guartz vein from Soholt Peaks. Note the distinct tectonic effect resulting subgrain elongation (top to bottom, shown by thin solid linens on the explanation figure), Böhm lamellae and deformation lamellae (left to right, shown by dotted bars) development. Chlorite is densely dotted, calcite is delineated by thick solid line, and opaque is solid (specimen 80011105B).*

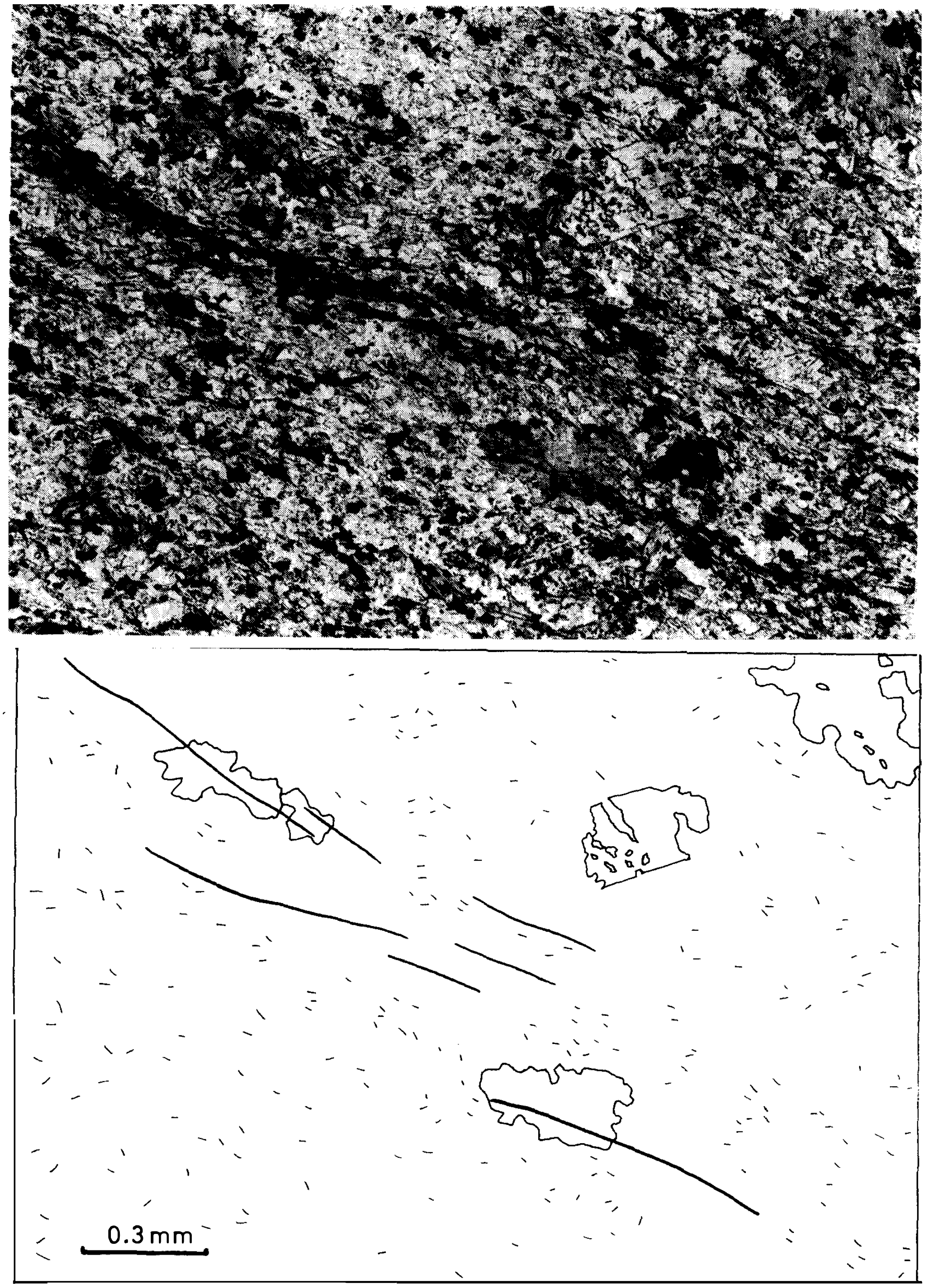


*Photo 20. Photomicrograph of a chloritoid-chlorite-sericite schist from the Wilson Nunataks. Chloritoid porphyroblasts overlap on the matrix muscovite (indicated partly by short, thin bars on the explanation figure), but afterwards are cut by new cleavages (heavy lines). Part of the chloritoid is altered to chlorite (specimen 79122902A).*

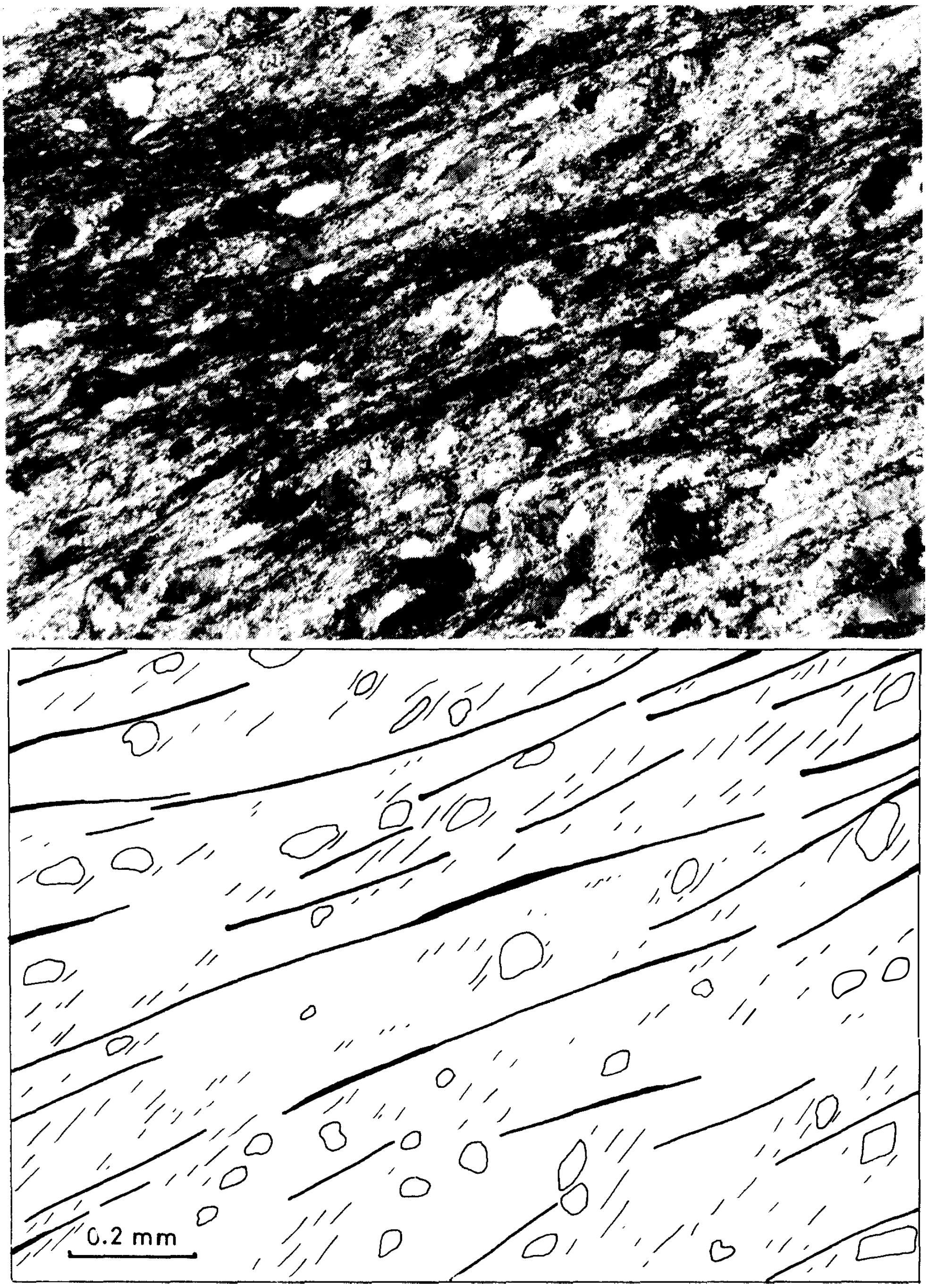


*Photo 21. Photomicrograph of a chlorite-sericite schist from the Wilson Nunataks. Late development of closely spaced cleavage (indicated parallel heavy lines on the explanation figure) cuts the preexistent schistosity made of nematoblastic muscovite (thin bars) (specimen 79123023).*