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Record 1973/10

THE STRUCTURAL GEOLOGY OF THE ARLTUNGA REGION, CENTRAL AUSTRALIA

by

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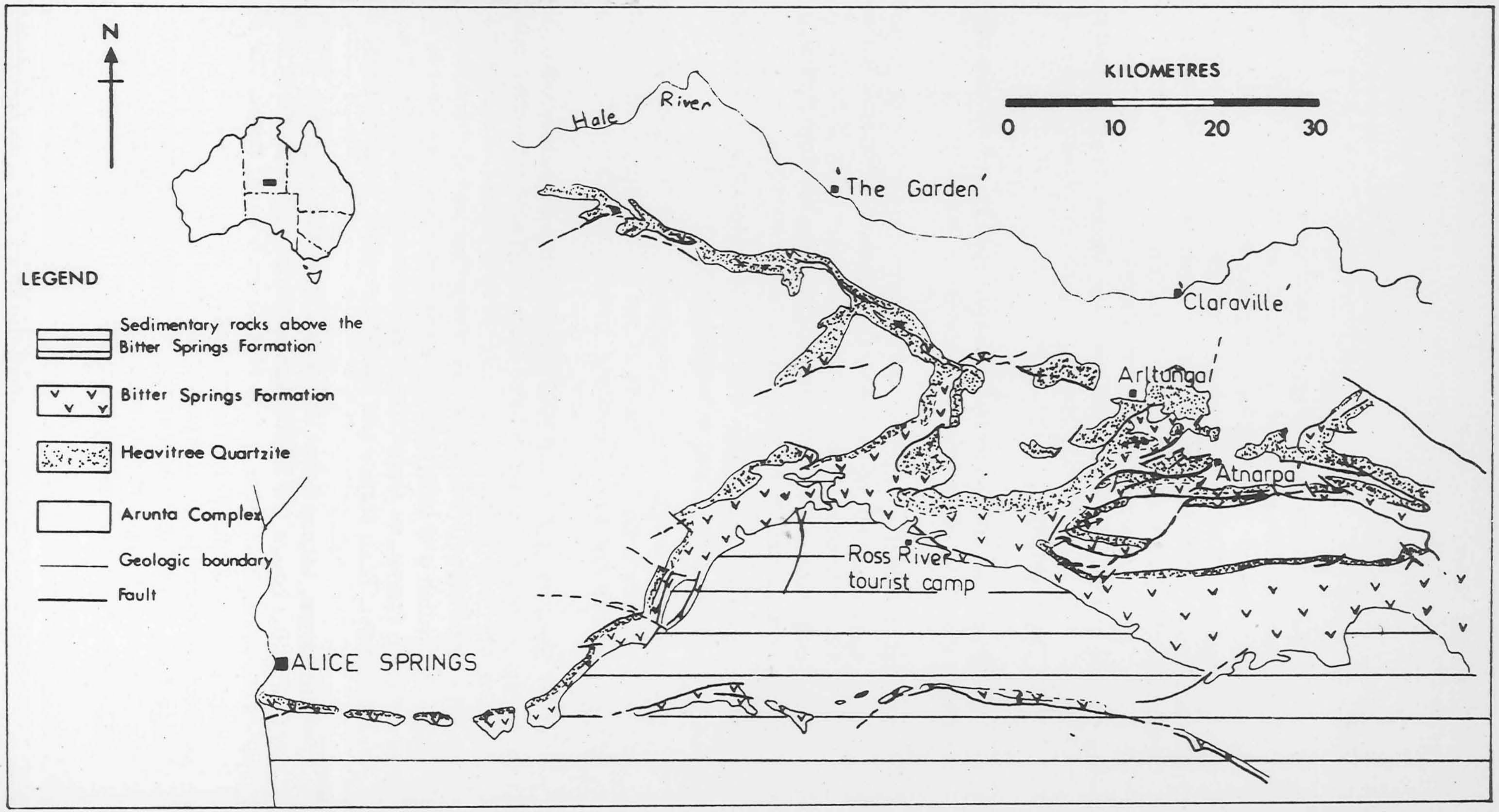
SUMMARY

Deformation of the Arunta Complex and its cover of sedimentary rocks began during late Devonian or early Carboniferous time. The basement behaved as a homogeneous tectonic unit, whereas the cover, deformed anisotropically owing to the presence of layers with different ductilities. A wedge of basement was driven southward into the Proterozoic succession, and younger sediments deformed independently above a decollement horizon in the Bitter Springs Formation.

The flattening effect of the basement nappe and a uniform lateral confining pressure imposed a penetrative planar fabric on the autochthonous basement and cover. Meridional relief produced a north-plunging mineral lineation and 'necked' conglomerate pebbles by ductile elongation. Strain analysis supports these observations, and suggests that the progressively increasing strain northward may represent a deformation path in the flattening field of plastic, irrotational strain.

Three phases of deformation are distinguished in some localities by overprinting criteria; together these may constitute a continuous deformation. When southward movement of the nappe was impeded, the direction of maximum shortening changed from vertical to meridional. It is considered that this resulted in a period of progressive deformation during which second-phase folds of various styles and orientations developed. The degree of anisotropy in the cover controlled the style of the folds, and in massive quartzite thrusting predominated. All structural elements were deformed in a final phase of non-planar, non-cylindrical folding.

Figure 1. Locality map and generalized geology of the Arltunga Nappe Complex. Geological boundaries taken from Alice Springs 1:250 000 Geological Sheet (First Edition, 1968), with some modification.



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INTRODUCTION

The Arltunga area (Fig. 1), situated about 100 km east-northeast of Alice Springs, forms part of the Arltunga Nappe Complex in the eastern MacDonnell Ranges. Detailed mapping and structural analysis on mesoscopic and macroscopic scales have elucidated the mode of basement and cover interaction during deformation. The content of this record has previously been submitted in a thesis as part requirement for the degree of B.Sc. (Honours) at the Australian National University. Logistic support during the course of field work was provided by the Bureau of Mineral Resources.

Previous Work

Forman (1971) invoked a major component of recumbent folding in the nappe complex. He advanced arguments based on:

a) stratigraphy. In the White Range region the deformed basal conglomerate of the Heavitree Quartzite occurs below the allochthonous Arunta Complex. Repetition of the stratigraphic sequence led Forman et al. (1967) to assume that major recumbent, isoclinal folding had occurred;

b) distribution of units. The map pattern (Fig. 1) suggested the existence of a major fold nappe;

c) inverted sedimentary structures. At a few localities such as Tommy's Gap and parts of the White Range, oscillation ripple marks and cross-bedding indicate inversion of the succession.

Stewart (1971) and Khan (1972) have completed detailed investigations in the nappe complex, which have suggested a progressive northward change of the strain, microfabric, and mesoscopic fabric. Khan, work ng east of Atnarpa homestead, concluded that thrusting was the dominant mechanism of nappe formation and that imbricate thrusts involving Arunta Complex rocks thrust over Heavitree Quartzite have been subsequently folded about east-trending axes. Both strain and fabric intensify towards thrusts. Detailed studies have revealed that when the fold-nappe hypothesis is applied to specific areas, inconsistencies arise. However, Forman (1971) envisaged overthrusting below the White Range Nappe and thus these studies do not preclude recumbent folding at a higher structural level. The structural interpretation of the White Range region is more critical to the fold-nappe hypothesis, since it is interpreted as part of the inverted limb of the White Range Nappe (Fig. 2). The results of mapping in this area are presented in this Record and suggest that major deformation resulted from thrusting rather than from recumbent folding.

STRATIGRAPHY

Basement Rocks

In the Arltunga area the basement cover interface is present both as thrust faults and as an unconformity in the autochthon. As is usual in such terrains (Watson, 1967) the basement deformed as a single, homogeneous, tectonic unit, and although the mode of deformation in the cover rocks, was controlled by ductility contrasts and anisotropy, they appear to have played no part in the deformation of the basement.

The basement consists predominantly of a strongly foliated medium to fine-grained gneiss composed of alkali feldspar (45%), quartz (33%), muscovite and biotite (12%), plagioclase (5%), and epidote (5%). Accessories include zircon, apatite, and sphene. Most of the alkali feldspar is microcline, which is microperthitic.

Other basement rocks in the area are metaquartzites, calc-silicate rocks, and a very fine-grained blue rock that occurs in pockets surrounded by gneiss. This rock is not foliated, and consists predominantly of hornblende and zoned plagioclase; it may represent an intrusion into the Arunta Complex.

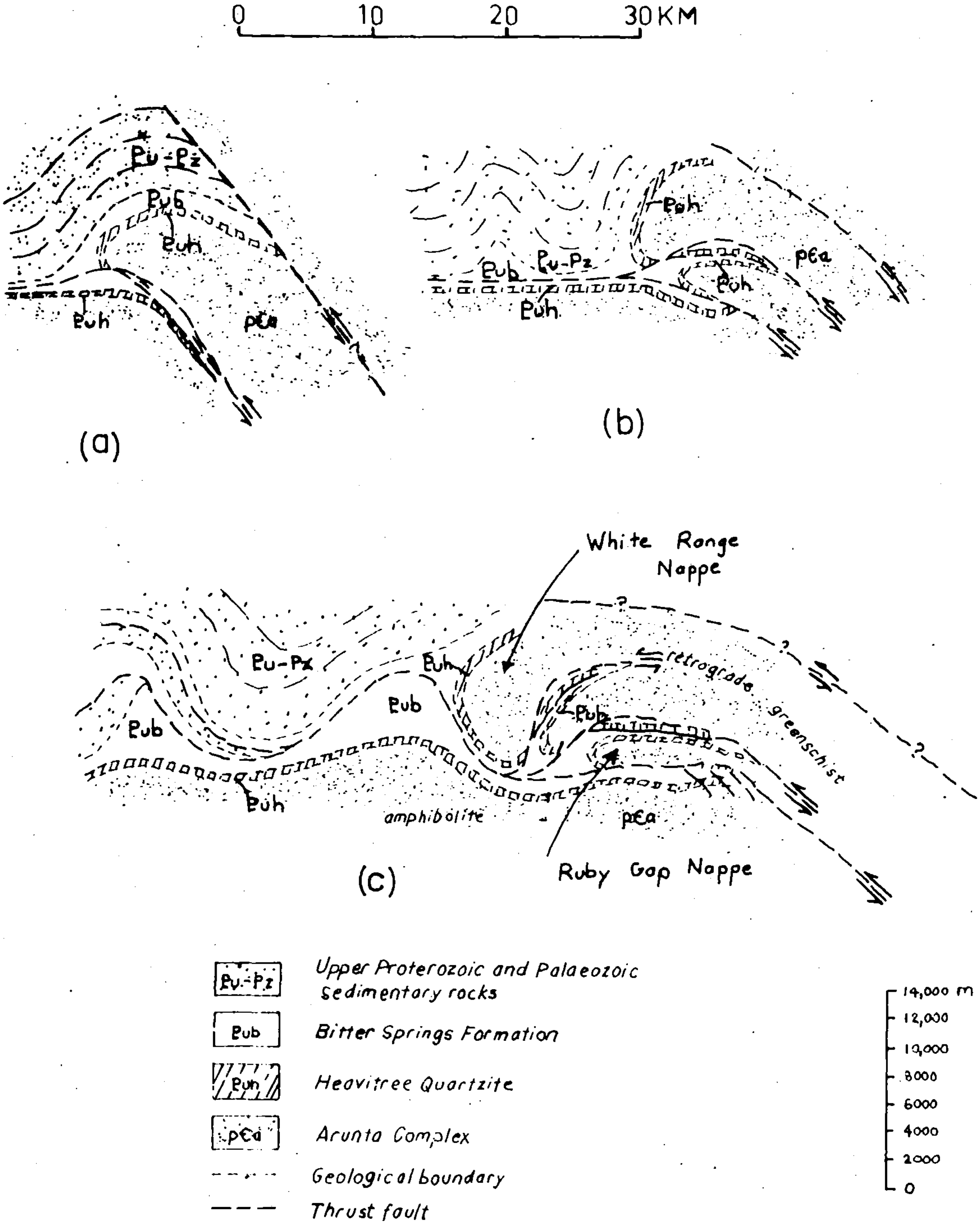
Metaquartzite occurs north of the White Range and south of Whisky Boot Hill, and is distinguished from the adjacent Heavitree Quartzite by the greater abundance of alkali feldspar (microcline) and the presence of biotite. Pale green amphibole and epidote are minor constituents. A calc-silicate rock composed of tremolite, plagioclase, calcite, clinozoisite, microcline, and quartz occurs locally south of the White Range.

The assemblages of the basement rocks are indicative of a period of regional metamorphism of amphibolite facies that probably occurred during the Arunta Orogeny about 1700 m.y. ago (Forman, 1971). The effects of the Palaeozoic dynamic metamorphism on both basement and cover are described later.

Cover Rocks

In the Arltunga area the cover is in thrust and normal stratigraphic relationship with the basement.

Heavitree Quartzite. Most hills and ranges are of Heavitree Quartzite. All units of the Heavitree Quartzite are represented in the Arltunga area, and, in addition, a conglomeratic member has been distinguished above the gritty quartzite member within the massive quartzite. The stratigraphic sequence within the Heavitree Quartzite used here (Fig. 3) is modified from a section measured by Khan (1972) in the range east of Atnarpa homestead. Establishment



<u>Figure 2.</u>

Stages in the evolution of the Arltunga Nappe Complex (after Forman, 1971).

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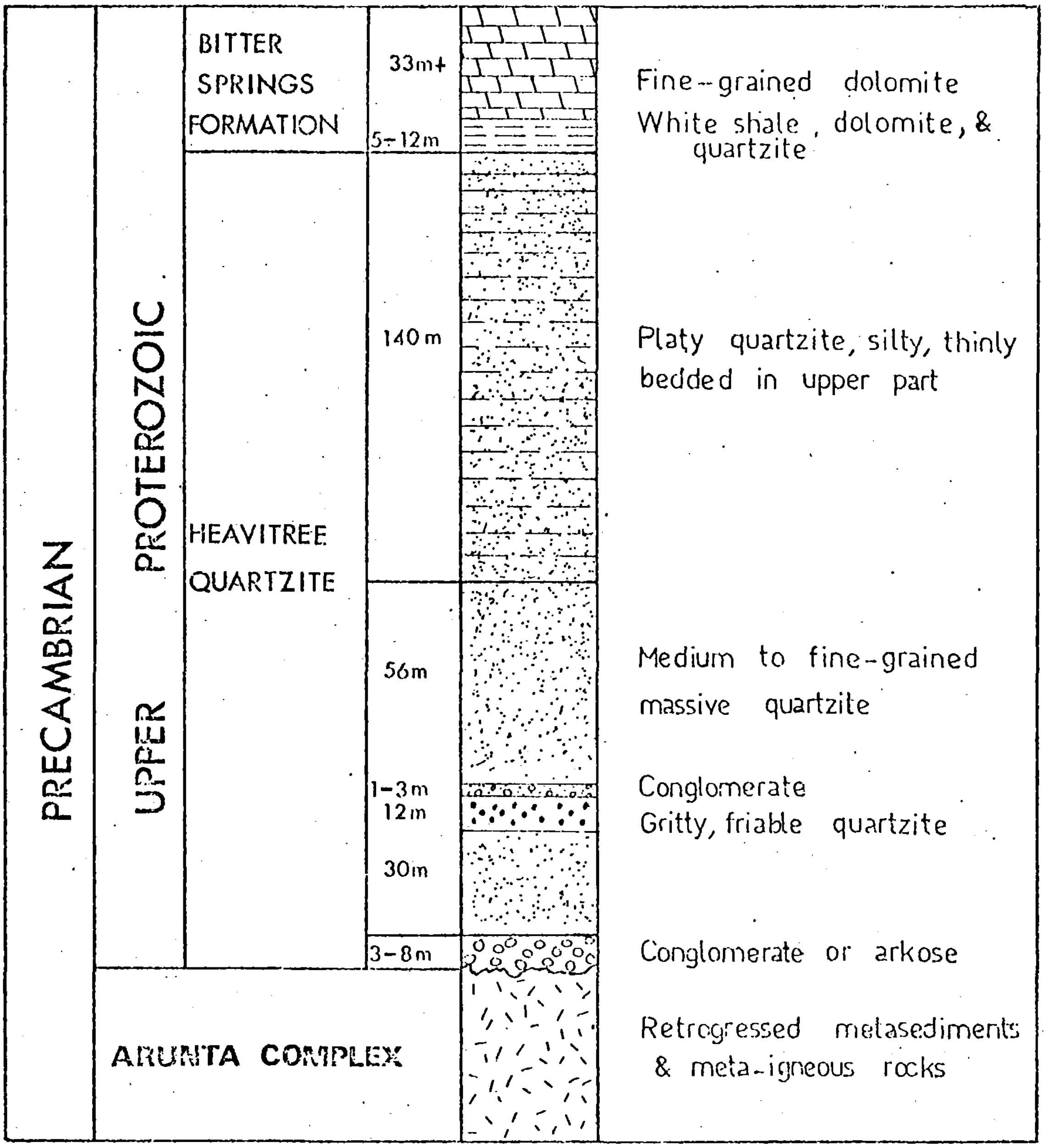

Figure 3 The stratigraphic succession in the Atnarpa Range region (modified after Khan, 1972)

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of the succession in the Heavitree Quartzite has greatly facilitated understanding of the structure. In the area west of Atnarpa homestead, the conglomeratic and gritty members provide useful marker beds.

The basal unit of the Heavitree Quartzite is a conglomerate or arkose; in most places it is about 6 m thick and lies unconformably on the basement northeast of Arltunga Bore. Although layering is known to have been transposed during the first phase of deformation, the irregular shapes and various compositions of the pebbles indicate that this unit is not a pseudoconglomerate. Most of the pebbles are quartzite, and the light grey to orange matrix consists of white mica, quartz, feldspar, and minor opaque minerals. The primary features of the conglomerate cannot be ascertained since it generally has a strongly developed phyllitic fabric (Plate 1B).

The massive part of the Heavitree Quartzite consists of a fine to medium-grained orthoquartzite. In the vicinity of Atnarpa Range the rocks are only slightly strained and the primary features of the quartzite can be recognized. Grains are well rounded and well sorted; the quartzite is texturally mature (Folk, 1968). Sericite and opaque minerals constitute a small fraction of the rock, which possesses a silica cement. The gritty member is 12 m thick and consists of well rounded, loosely cemented grains up to 2 mm in diameter and enveloped by a quartz overgrowth. The conglomeratic member consists of well sorted white quartzite pebbles up to 6 cm in diameter in a coarse-grained quartzitic matrix, and averages 1.5 m thick.

The uppermost unit of the Heavitree Quartzite is a platy fine-grained quartzite with a maximum thickness of 140 m. It is bluish-grey, but weathers purple.

Sedimentary structures are common in the massive and platy quartzites. Symmetrical cuspate ripple marks, 1.5 cm in amplitude and wavelength, are ubiquitous in both, and are indicative of shallow-water wave action (Conybeare & Crook, 1968). Cross-bedding is common in medium-grained parts of the massive quartzite. The thickness of the cross-bedded units averages about 50 cm, and the cross-stratification is of the Omikron type (Allen, 1963). Structures similar to polygonal mud-crack moulds have been observed in all three units of the Heavitree Quartzite but may be synaeresis cracks (White, 1961). Cross-bedding and ripple marks were widely used in the southern part of the area to determine facing direction, but in the northern part of the White Range all primary structures have been obliterated by the new fabric imposed during the first phase of deformation.

Bitter Springs Formation. Only part of the Bitter Springs Formation is represented in the Arltunga area, and this has not been subdivided because it is highly deformed and poorly exposed. The dominant rock-type is a very fine-grained grey dolomite which weathers brown; calcrete is commonly developed at the surface. Thin beds of quartzite and greyish-white shale are intercalated with the dolomite. The shales appear to have provided decollement horizons during thrusting, especially a soft white shale near the base of the sequence. Quartz, feldspar, sericite, and opaque minerals are the dominant minerals of the shales.

The sedimentary structures and rock types suggest that the cover rocks were deposited in a shallow marine environment.

STRUCTURE

Thrust Faults

Four structural levels are recognized above the autochthonous basement, and a structural level map (Fig. 4) has been prepared to indicate the relative distribution of the different thrust sheets; the sheets are numbered in ascending order above the autochthon.

Both autochthonous basement and cover in the northern part of the White Range possess a well developed fabric which has overprinted and obliterated the primary features of the quartzite, and so facing directions cannot be determined in this area.

In the Atnarpa Range area the outcrop pattern of the Heavitree Quartzite is the result of folding of the thrust sheets. Farther north, in the Whisky Boot Hill and Diomedes Hill regions, the thrust planes are less intensely folded, and in the southeastern part of the White Range they are only slightly warped.

Thrust sheet 1. The sole thrust is exposed in Atnarpa Range, at Diomedes Hill, and in the southeastern part of the White Range. Abundant cross-bedding and ripple marks indicate that the units of the lowest thrust sheet face upwards, and that the sequence is repeated by overthrusting. In the Atnarpa Range, folding about approximately east-trending axes and erosion have exposed the platy quartzite of the autochthon along strike as a tectonic window (Map 1, sections DD' & EE') overthrust by the gritty unit of the massive Heavitree Quartzite. Tectonic windows exposing autochthonous platy quartzite also occur on Diomedes Hill and, in the southeast of the White Range, massive

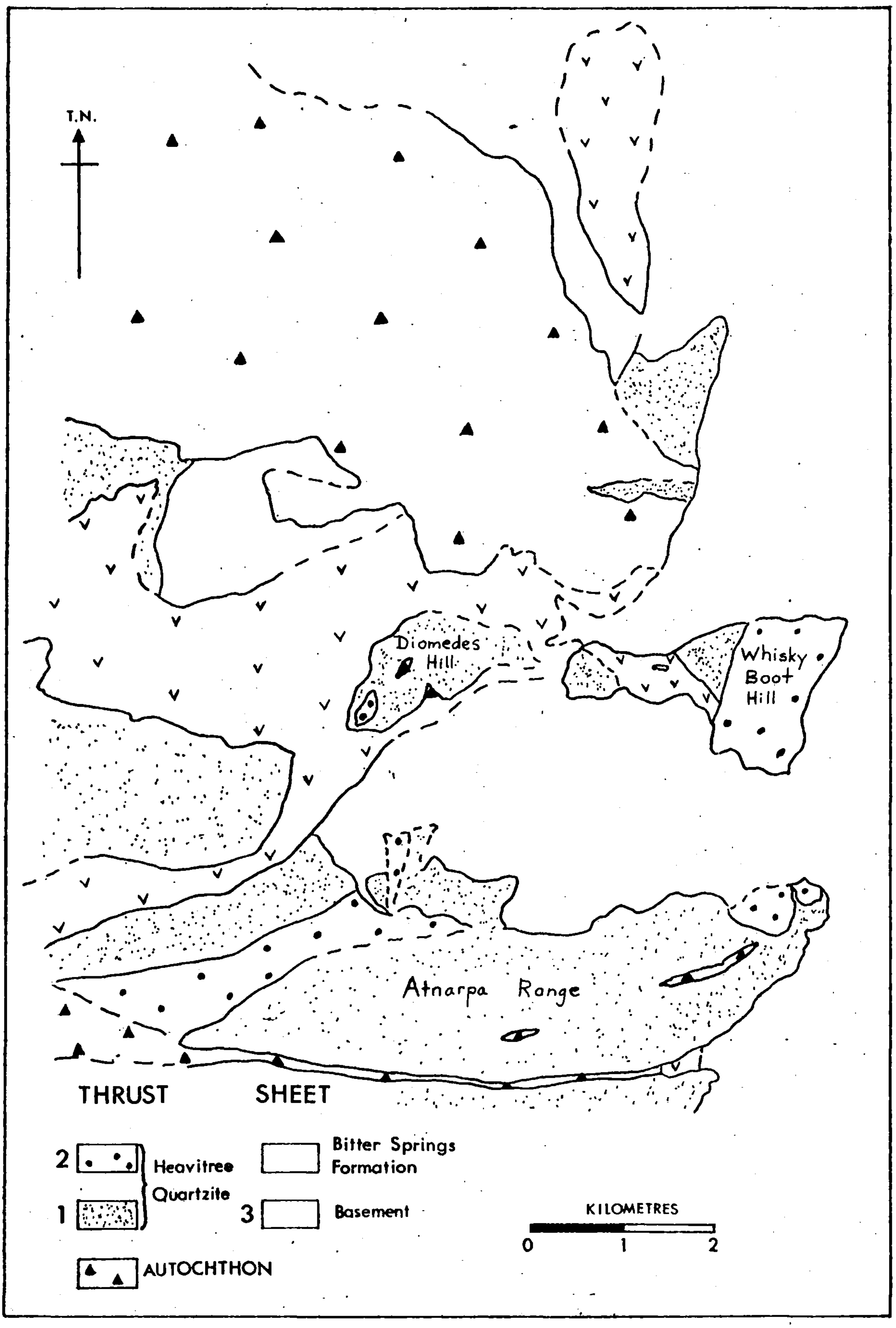


Figure 4 Structural level map of the Arltunga region. The thrust sheets are numbered in ascending order above the autochthon.

Plate 1

A. The basal arkose of thrust sheet 2 thrust over massive Heavitree Quartzite in the northern part of Whisky Boot Hill.

B. Pebbles in the basal conglomerate of the White Range elongated parallel to the foliation, S_1, and warped by subsequent deformation.

C. Intrafolial* folds in the basement east of the White Range. Although these folds are now parallel to the basement foliation, S_{n+1}, they may have been transposed during a much earlier deformation (see text).

* This term is used in the same sense as Turner & Weiss (1963) and describes relict folded surfaces that have been transposed into a later foliation.

A

B

C

quartzite is thrust over autochthonous quartzite. The massive quartzite of thrust sheet 1 constitutes the greater part of Atnarpa Range, where the sole thrust dips steeply north or south (Map 1, section DD'). The approximate east-trending strike of this level is emphasized by the thin conglomeratic unit of the massive Heavitree Quartzite. On the northern flank of Atnarpa Range basal conglomerate of thrust sheet 1 is exposed at one locality below the massive quartzite.

In the structural sections the sole thrust is shown dipping below allochthonous basement to reappear in the vicinity of Diomedes Hill. A root zone for the sole thrust probably exists north of the White Range near the basement-cover interface.

Small areas of white shale of the Bitter Springs Formation are associated with the autochthonous platy quartzite on Diomeses Hill, although elsewhere it is directly overlain by the gritty member, suggesting that the upper Heavitree Quartzite and the basal shales of the Bitter Springs Formation have acted as décollement horizons for the sole thrust.

Thrust sheet 2. A sheet of basal and massive Heavitree Quartzite is thrust over sheet 1 in the vicinities of Whisky Boot Hill (Plate 1A; map 1, section BB'), and Atnarpa Range (Map 1, section CC' and EE').

Penetrative foliation is not associated with the interface between thrust sheets 1 and 2 in Atnarpa Range, and the rocks in this zone are best described as cataclasites (Spry, 1969). However, near Whisky Boot Hill a thin mylonite zone has formed at the contact between the two sheets. At this locality the overthrust sheet is arkosic or massive toward the base (Plate 1A) and passes upward into a medium-grained quartzite. The basal arkosic unit of thrust sheet 2 is represented as a tectonic klippe on Diomedes Hill and also occurs in Atnarpa Range near Atnarpa homestead.

Cross-bedding and ripple marks in the western part of Atnarpa Range and at Whisky Boot Hill indicate that the rocks of thrust sheet 2 face upwards.

A fine-grained mylonitic rock occurs in the thrust zone between sheets 1 and 2. Examination of a thin section reveals this to be the deformed gritty member of the massive Heavitree Quartzite; overgrowths can still be recognized around sheared and flattened quartz grains. Thus, although within the Heavitree Quartzite the thrusting appears generally to have resulted in cataclasis, at the interface of the two thrust sheets the gritty unit may have acted as a décollement zone in places.

Thrust sheet 3. Allochthonous basement of thrust sheet 3 crops out between Atnarpa Range and the White Range.

The sheet shows both underthrust and overthrust relationships with the cover at different localities. Thus, the basement sheet overthrusts the Heavitree Quartzite of Atnarpa Range, Whisky Boot Hill, and the eastern part of the White Range, but is structurally below the Bitter Springs Formation between Atnarpa Range and the White Range (Fig. 4), as evidenced by the presence of hills of basement capped by Bitter Springs Formation. At a locality on the northwestern flank of Atnarpa Range the basement sheet occurs below quartzite of the middle Heavitree unit, a layer of mylonite marking the interface. Sedimentary structures indicate that the quartzite above the basement faces upwards. Normal overthrusting cannot explain these structural relationships as it requires the units between the thrusts to maintain their normal stratigraphic order. Recumbent folding could be invoked if it is assumed that the quartzite enveloping a basement core behaved in such a brittle fashion that macroscopic boudinage occurred, allowing rocks of the Bitter Springs Formation to be emplaced structurally above the basement. Then, whereas in some parts of the nappe quartzite could occur as 'tectonic fish' within the Bitter Springs Formation, in other areas the normal basement cover interface could be preserved. However, on this interpretation, the Heavitree Quartzite occurring below the allochthonous basement in other localities must be interpreted as an inverted limb of the fold nappe. That recumbent folding on a macroscopic scale has not occurred is suggested by the consistent upward facing as observed in the other thrust sheets and by the observation of increasing intensity of both penetrative and cataclastic deformation towards the interface.

The trace of the basement thrust is thought to be marked approximately by the boundary between the metaquartzite north of the White Range and the Heavitree Quartzite; to the northwest of the White Range the fault trace trends northwest. The presence of a more intense fabric within both autochthonous basement and cover in this region tends to support this interpretation. Rocks of the Bitter Springs Formation east of the White Range are more strongly foliated than those south of the White Range. A subparallel foliation in the allochthonous basement east of the White Range suggests that it is structurally below the adjacent Bitter Springs unit.

The style of thrust deformation within the cover has been strongly dependent upon the lithological contrasts of various units in the succession. In contrast, the allochthonous basement behaved as a tectonic unit during the basement cover interaction, which apparently proceeded in such a manner that the order of stratigraphic succession in the cover was disrupted.

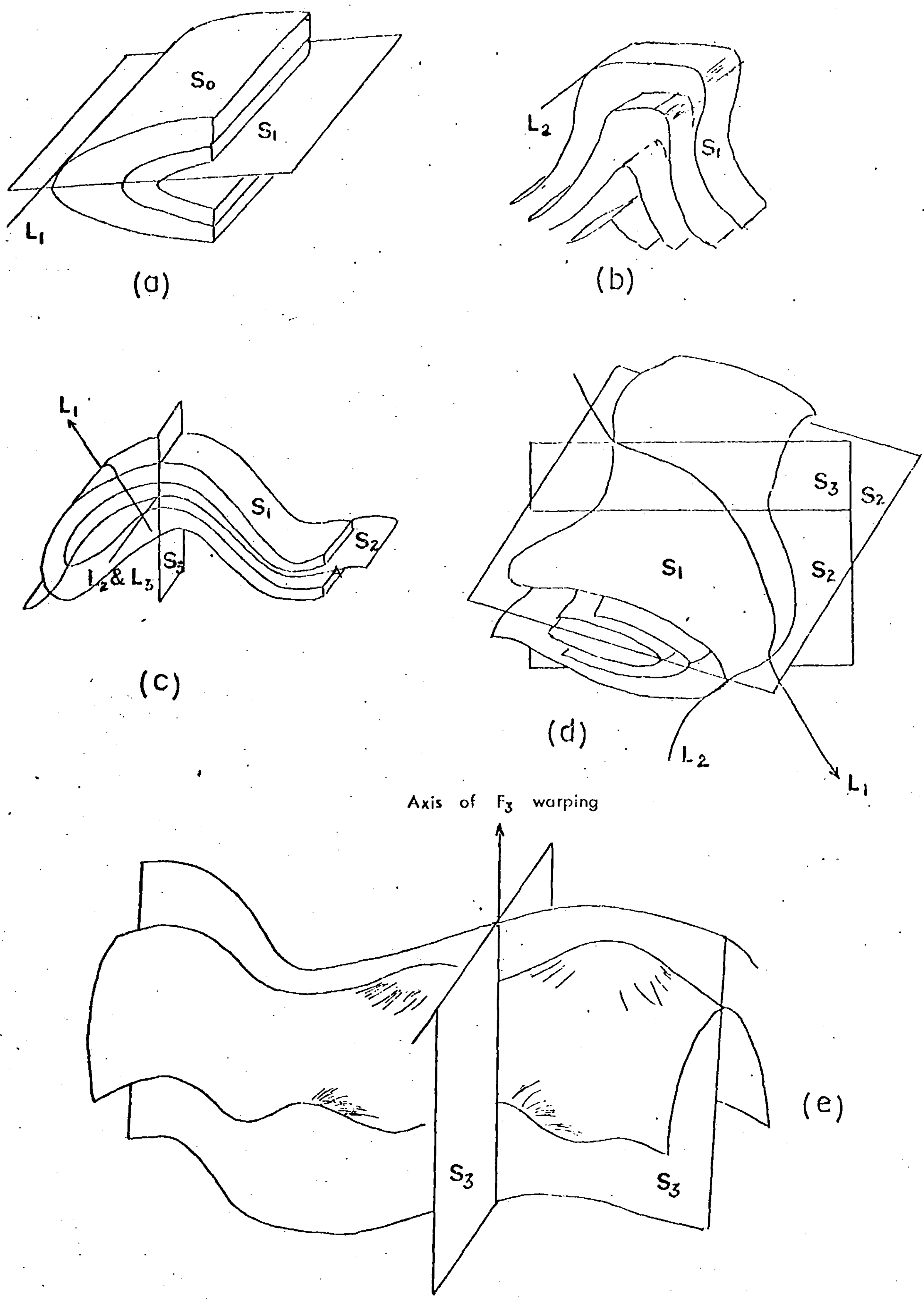


Figure 5.

Schematic representation of the structural relationships. S_2 and S_3 are the axial surfaces for the second and third-phase folds. (a) First-phase elements. (b, c, & d) Second-phase folds. (e) Non-planar, non-cylindrical third-phase folding.

Structural Elements

In order to ascertain the relationship of folding and thrusting, the structural data for each thrust sheet have been plotted separately. However, the autochthon and thrust sheet 1 have been divided into subareas so that the effects of later macroscopic warping, which deformed the thrust sheets as a pile, can be evaluated by tracing the change in attitude of structures from one area to another (Map 2).

The unconformity between autochthonous basement and cover northeast of Arltunga Bore has been folded during a period of deformation that postdated the thrusting and locally inverted the sequence in the western part of the White Range. The nature of this folding is unknown because of insufficient field data. Three phases of folding are recognized in the Arltunga area; they are defined by refolding or overprinting criteria. The first phase accompanied the major thrusting episode during which a new fabric was imposed on both allochthonous basement and cover. This fabric was overprinted by folds of various styles and orientations during the second phase of deformation. Finally, previous structural elements were warped during a phase of non-planar, non-cylindrical folding that postdated the thrusting.

Table 1 summarizes the essential features of the structural elements and Figure 5 shows their relationships.

Bedding, S_o. Lithological layering associated with primary sedimentation features is recognizable in the Heavitree Quartzite of Atnarpa Range but is obliterated farther north by the fabric associated with the first phase of deformation. Abundant sedimentary structures and well rounded grains in thickly-bedded quartzite testify to the weak deformation present in Atnarpa Range. Bedding is only locally observed in rocks of the Bitter Springs Formation because they deformed more readily than the quartzite. Layering within the upper platy unit of the Heavitree Quartzite appears to have controlled the subsequent flexural-slip folding in the southern part of Atnarpa Range.

Lineation, L_1. The following styles of lineation have been recognized and assigned to the first-phase deformation:

a) A penetrative lineation due to the elongation of quartz grains and genetically related to a foliation, S_1, imposed by strain. This lineation is present throughout the entire area, but is better developed north of Atnarpa Range. A distinct correlation exists between the degree of elongation of the quartz grains and the degree of preferred orientation of the long axes of the grains, both of which

Table 1. Summary of structures in the basement and cover

COVER			BASEMENT		
Structural element	Style	Overprinting relationship	Structural element*	Style	Overprinting relationship
S_o	Lithological layering	Folded by F_1, F_2, & F_3	Sn	Unknown	Possibly transposed by S_{n+1}
S_1	Dimensional orientation of strained quartz grains; metamorphic segregation	Folded by F_2 & F_3; kinked & crenulated by L_2	S_{n+1}	Metamorphic segregation; dimensional orientation of quartz	Folded by F_{n+2} & F_{n+3} crenulated by L_{n+2}
L_1	Quartz elongation; rodding; striping; pebble elongation	Folded by F_2 & F_3	L_{n+1}	Mineral elongation; striping	Folded by F_{n+2} & F_{n+3}
F_1	Tight, recumbent, flattened concentric	Rarely observed but may be obliterated by F_2	Not observed	-	-
L_2	Crenulation; weak mineral elongation	Locally refolded by F_3	L_{n+2}	Crenulation; kinking	Locally refolded by F_3
F_2	Isoclinal, reclined or recumbent; chevron; box, conjugate, kinks; open, flattened concentric	Locally refolded or disrupted by F_3	F_{n+2}	Isoclinal, reclined or recumbent; kinks	Locally refolded by F_3
F_3	Non-planar, non-cylindrical	-	F_{n+3}	Non-planar non-cylindrical	-

* The subscript, n, takes into account any pre-existing fabric in the basement.

increase progressively northward. The shape of the quartz grains varies from oblate to prolate ellipsoidal throughout the area. In the White Range region, where subsequent deformations had little effect, the lineation plunges about 15° north;

b) small quartz rods, parallel to local fold axes, are present in the gritty quartzite member in the southwestern part of the White Range, and appear to be the result of folding and attenuation of quartzite layers (Wilson, 1953);

c) a preferred orientation of the long axes of deformed pebbles in the basal conglomerate of the Heavitree Quartzite exists north of Atnarpa Range but is especially well developed in the White Range. It is parallel to the lineation defined by the long axes of quartz grains in the same rocks, and both are commonly associated with 'necking' probably caused by ductile flow parallel to the lineation direction;

d) a weak lineation of 'striping' exists in the quartzite in the eastern part of Atnarpa Range, where a first-phase fabric is locally developed, and in the allochthonous basement, where it is defined by a colour banding.

The quartz grain elongation is the dominant lineation, the striping being only of local importance. Slickensides in Atnarpa Range may be L_1 lineations, but it is possible that they formed during later flexural-slip folding.

Foliation, S_1 & S_{n+1}. A penetrative foliation, S_1, consists of a flattening fabric in the quartzite defined by flattened quartz grains, which gradually changes to a mylonitic layering or fluxion structure in the vicinity of thrust faults. Fluxion structure is also present in the basement gneiss, and is defined by alternating layers of micaceous and quartzo-feldspathic material enveloping relict feldspar augen. The foliation within the Heavitree Quartzite is most intense in the White Range, where it dips about 15° north, parallel to L_1 (Map 2, subarea 6). In other areas the poles to foliation have been dispersed in a partial girdle because of subsequent folding. Both S_1 and L_1 are present in all thrust sheets, and become more intense northward and nearer the thrust contacts.

Within the allochthonous basement a metamorphic segregation foliation, S_{n+1}, exists and is considered to be equivalent to S_1 of the cover since:

a) it is defined by greenschist facies minerals that formed during retrogression of the basement during nappe emplacement;

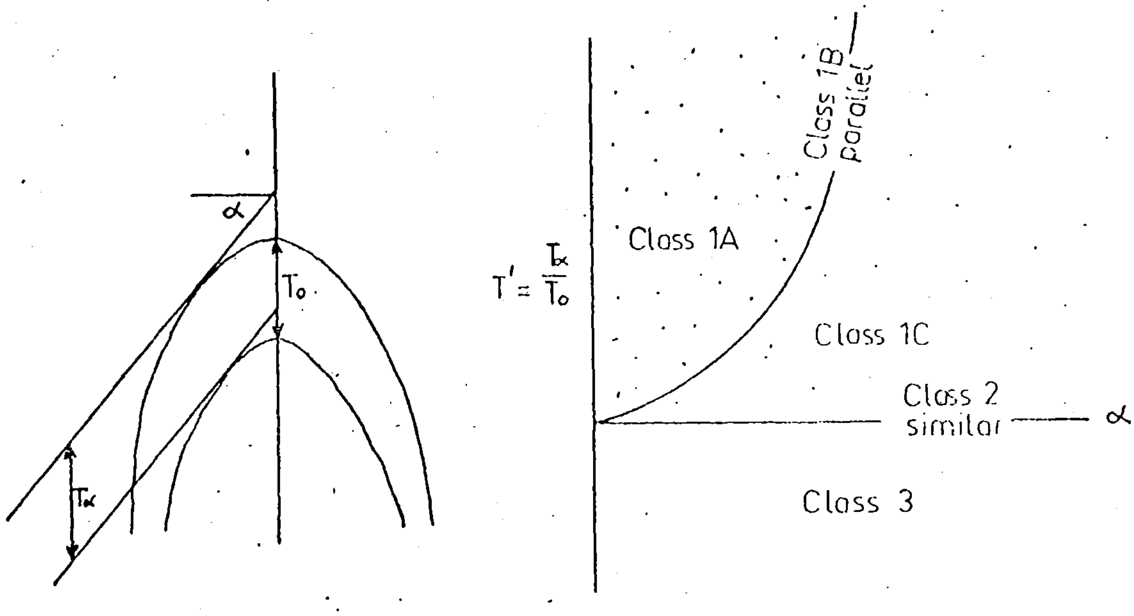
b) it is parallel to the foliation in contiguous cover rocks;

c) a weak flattening fabric (Flinn, 1965) also occurs in the quartzo-feldspathic layers of the basement foliation; the fabric in both cover and basement may have resulted during the same deformation.

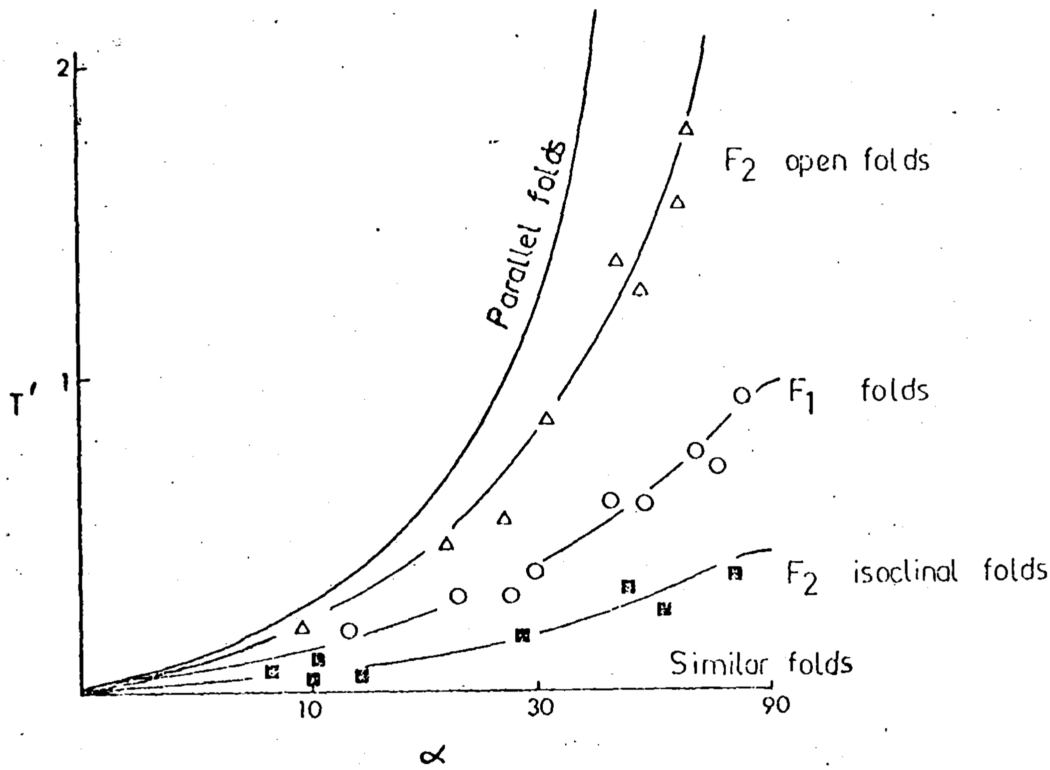
However, it is only the association of the retrogressive assemblage with the basement foliation that necessitates the equivalence of the two fabrics; the retrogression provides a basis for correlation. A fabric with the same attitude as that in the cover could be relict from a previous deformation and, in recognition of this, the term F_{n+1} is used for the first-phase deformation in the basement. Intrafolial folds (Turner & Weiss, 1963) are associated with the basement foliation (S_{n+1}) in localities adjacent to the White Range (Plate 1C), and generally represent quartzo-feldspathic layers that have been transposed by a foliation. As Park (1969) has pointed out, the relationship of these folds to the youngest foliation is indeterminate, since it is conceivable that intrafolial folds of successive generations may converge during a later phase of transposition. Thus, it is impossible to determine whether the present foliation, S_{n+1}, is axial-plane to F_{n+1} folds in which the transposition process has simply proceeded to an advanced state. If the intrafolial folds formed during the Arunta Orogeny, the possibility also exists that, during the deformation associated with nappe emplacement, the basement was reactivated along an older fabric. Watson (1967) has argued that, in view of the different rheological properties of basement and cover, reactivation along an old fabric is unlikely.

The S_1 foliation varies in style according to the rock type in which it is developed, and in the fine-grained dolomite of the Bitter Springs Formation it is completely absent. In the shales of this formation the foliation is defined by the segregation of sericitic and quartzo-feldspathic layers about 2 mm thick. In the metamorphic segregation layers of the basement, biotite commonly forms layers which are thicker than those observed in the shales. This S_1 foliation contrasts with the flattening fabric of the Heavitree Quartzite, in which the long and intermediate axes of deformed quartz grains define the foliation. These differences may be explained by the heterogeneity of the respective units, since different rock types may be expected to respond differently to the same flattening deformation (Williams, 1972).

Folds, F_1. Very few folds associated with the first-phase fabric have been observed. In the southwest of the White Range, however, S_1 is axial-plane to tight recumbent folds (tightness refers to the interlimb angle,



(a)



(b)

Figure 6

(a) The geometrical classification of folds using thickness measured parallel to the axial plane (after Ramsay, 1967). (b) Axial-plane thickness plots for first and second-phase folds in the Arltunga region.

Fleuty, 1964). In the classification of Ramsay (1967), the folds belong to class 1C, close to the field of similar style geometry (Fig. 6b). Quartz rodding is the only lineation parallel to these fold axes. The paucity of F_1 folds may be due to the nature of the first-phase deformation, the subsequent obliteration of F_1 folds by transposition in S_1 associated with the flattening strain, or the subsequent unfolding of F_1 folds.

Lineation, L_2. The most prominent second-phase lineation is a crenulation of the S_1 and S_{n+1} foliations parallel to second-phase fold axes in cover and basement and at all structure levels. Generally, there is no transposition of the S_1 foliation and the lineation is only a gentle plication. At two localities south of Whisky Boot Hill, the basement foliation has been deformed into small cusp-shaped folds with a regular amplitude of 5 cm and axes plunging 30° north. In the shales of the Bitter Springs Formation, irregular crenulations of the micaceous layers are visible in thin section. At some localities in the south of Atnarpa Range the crenulations grade imperceptibly into small asymmetrical k nks verging* both north and south.

A weak quartz-elongation lineation parallel to F_2 fold axes is present in a few places in the Bitter Springs Formation and the Heavitree Quartzite, but characteristically gives way to the more intense, refolded L_1 lineation within the same outcrop.

Folds, F_2. Folds of various styles and orientations refold and overprint the structural elements of the first-phase deformation, and consequently belong to a later phase of deformation (Fig. 7).

Isoclinal, reclined, or recumbent folds are ubiquitous in the south-eastern part of the White Range (Plates 2A, & 3B), where they are closely associated with box or conjugate folds in the platy quartzite (Fig. 7a). The isoclinal folds are bullet-shaped in profile, and in some localities the limbs are boudinaged (Plate 2B). Thickness measurements indicate that the folds plot in the field of strong flattening (type 1C) close to the similar model (Fig. 6B). Generally, amplitudes are about 3 m, but some macroscopic isoclinal folds that refold the first-phase lineation belong to the F_2 phase. Invariably the sense of vergence is southward, although some isoclinal folds verge northward. South-verging, inclined, isoclinal folds are present in the eastern part of the White Range, where they are associated with a crenulation lineation or a weak mineral elongation. This particular F_2 style is found only in the platy quartzite, foliated quartzite, or rocks of the Bitter Springs Formation, and is completely absent from the quartzite of Atnarpa Range in spite of the existence of other F_2 structures there. A penetrative S_2 axial

* The vergence of a fold is the direction of the normal to its axis lying in the fold-axial plane.

surface has not been imposed, although locally a weak fracture cleavage is developed. Boudinage is present in the southeastern part of the White Range, and is of the 'pinch and swell' type (Fig. 7a) expected in a material of near uniform ductility. Ductile material surrounding the boudins has flowed around and between the boudins, thereby deforming the older S_1 foliation. Boudin axes are subparallel to the axes of folds in which they are developed.

A different style of second-phase folds occurs in the quartzite of Whisky Boot Hill and Atnarpa Range (Fig. 7b; plate 3A), where S_1 foliation is absent or subordinate to bedding. In profile these folds are open and nearly parallel with only slight flattening (Fig. 6b), and are reclined with plunges of about 30°.

Box folds with amplitudes of about 1 m and well rounded hinges change style downward into chevron folds (Fig. 7c; plate 2C) which decrease in amplitude toward a décollement. Conjugate and reverse kink folds (Fig. 7d) are common in the southern part of the White Range; they differ from box folds in that successive surfaces maintain an identical form (see also Ramsay, 1967, p. 357) although all gradations between the two are observed. Shearing has occurred subparallel to one of the axial planes of some box folds, suggesting that at least part of the F_2 deformation may have taken place under brittle conditions. In the foliated middle Heavitree Quartzite unit near Atnarpa homestead, the S_1 foliation has been deflected into broad box folds with large hinge curvatures. The L_2 lineation is commonly subparallel to the hinges of conjugate and box folds.

Whether kinks developed in the limbs of F_2 folds belong to the second phase or a subsequent deformation cannot be determined at most localities, as no penetrative F_2 fabric exists that permits differentiation of phases on the basis of refolding criteria; the parallelism of kink axes with F_2 folds is insufficient evidence for ascribing them to the second phase deformation. However, a kink phase of this generation (Fig. 7e) can be established in some localities, where subsequent folding has warped both kink axes and contiguous F_2 fold axes. In such folds the assymetrical kink bands are about 2 cm in width and verge both north and south.

Rickard (1971) has proposed a classification of fold orientations in which the essential parameters are plotted on a triangular diagram; this has been used to distinguish three of the F_2 fold styles (Fig. 8). The isoclinal folds are slightly scattered within the recumbent to reclined fields but are easily distinguished from the open folds, which are well grouped with an average plunge of 30° within the reclined and inclined fields. Conjugate and box folds have a small plunge, and are slightly scattered in the upright fold field.

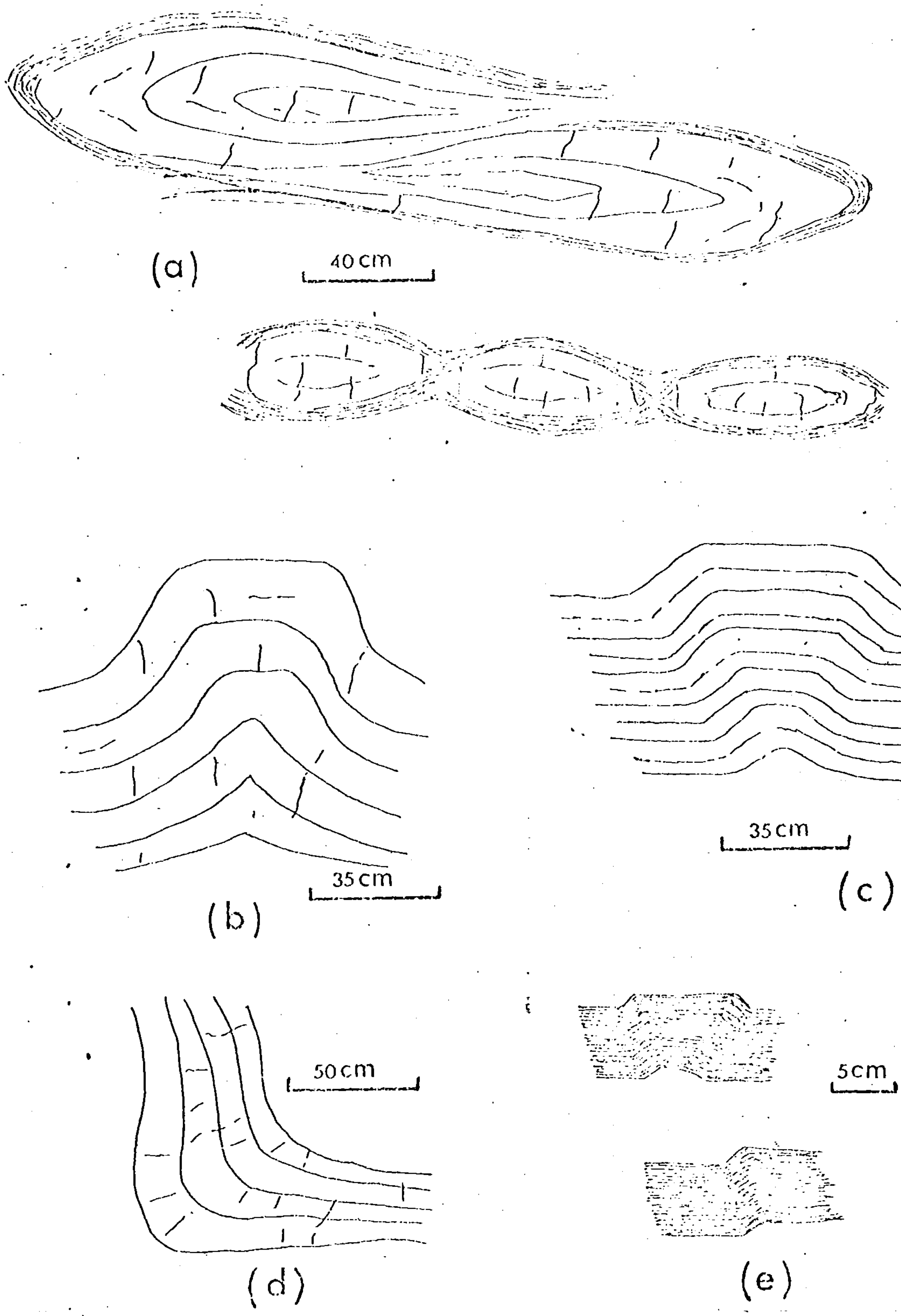


Figure 7.

F_2 fold styles. All drawings are profiles and the folded surface is S_1 or S_0. (a) Isoclinal fold in the upper Heavitree Quartzite and associated boudinage. (b) and (c) Box and conjugate folds in the platy quartzite. (d) Open fold in massive Heavitree Quartzite. (e) Kink bands in the upper and basal quartzites.

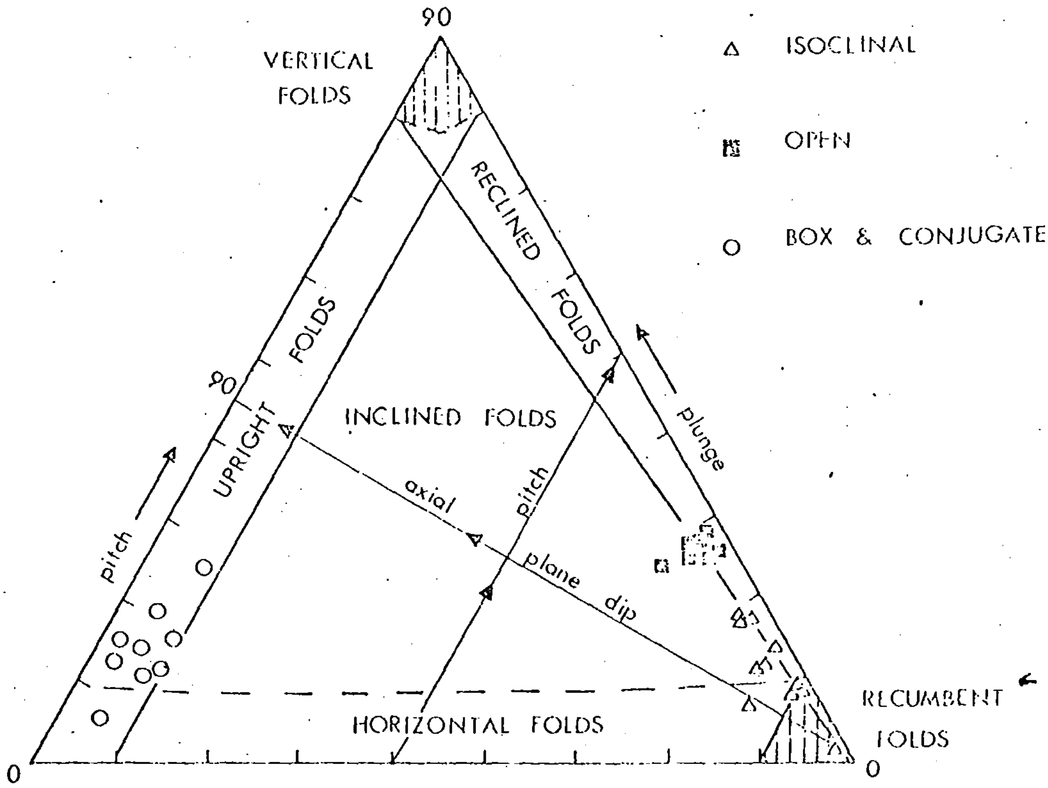


Figure 8

Separation of three of the second-phase fold styles using a D.P.P. diagram (after Rickard, 1971).

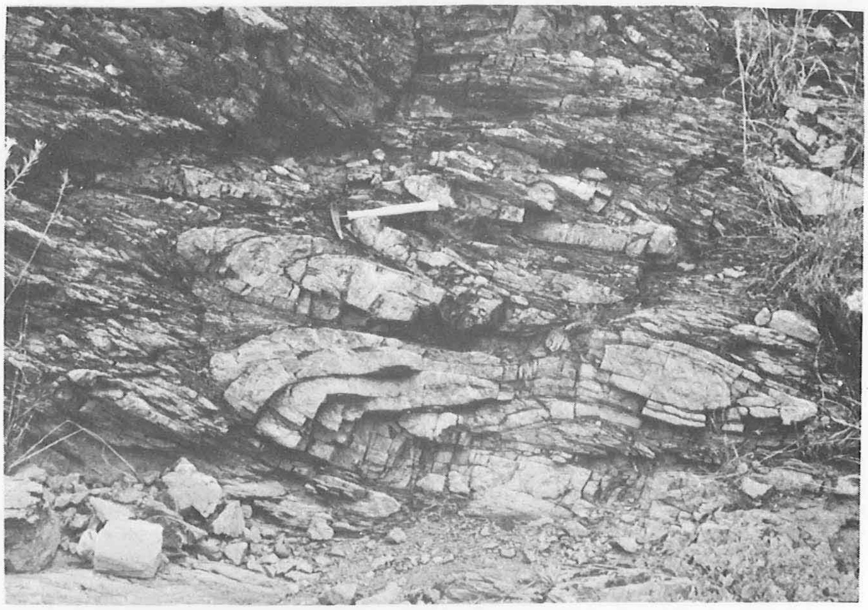
To accompany Records 1973/10 F53/A14/166

Plate 2

A. Second-phase isoclinal folds in the upper unit of the Heavitree Quartzite in the southeastern part of the White Range. This style varies in orientation from reclined to recumbent.

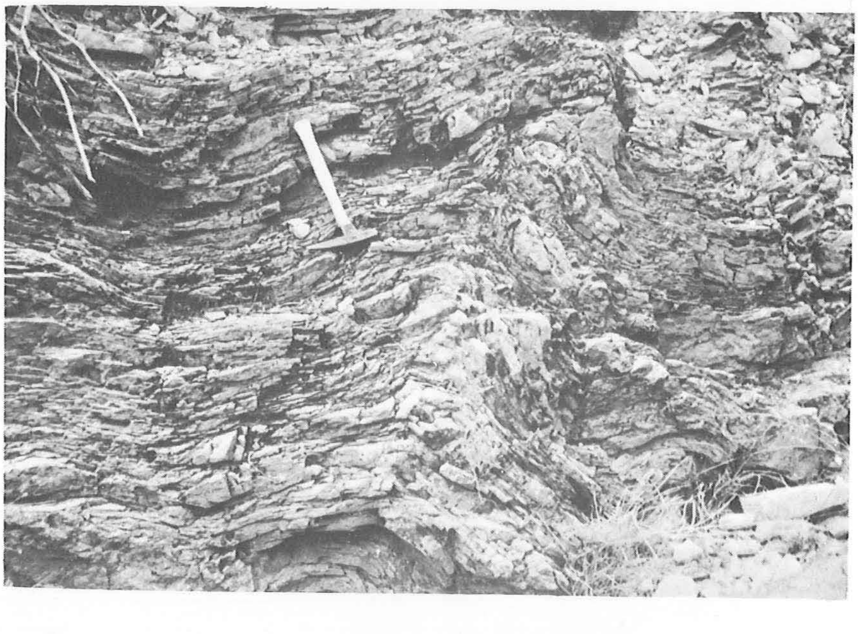
B. Boudinage developed during the second phase of deformation in the upper unit of the Heavitree Quartzite of the White Range. Elongation has occurred parallel to the first-phase foliation (S_1).

C. Box fold in the platy unit of the Heavitree Quartzite in the southern part of the White Range. The amplitude of folding decreases downward toward a décollement.



A

B



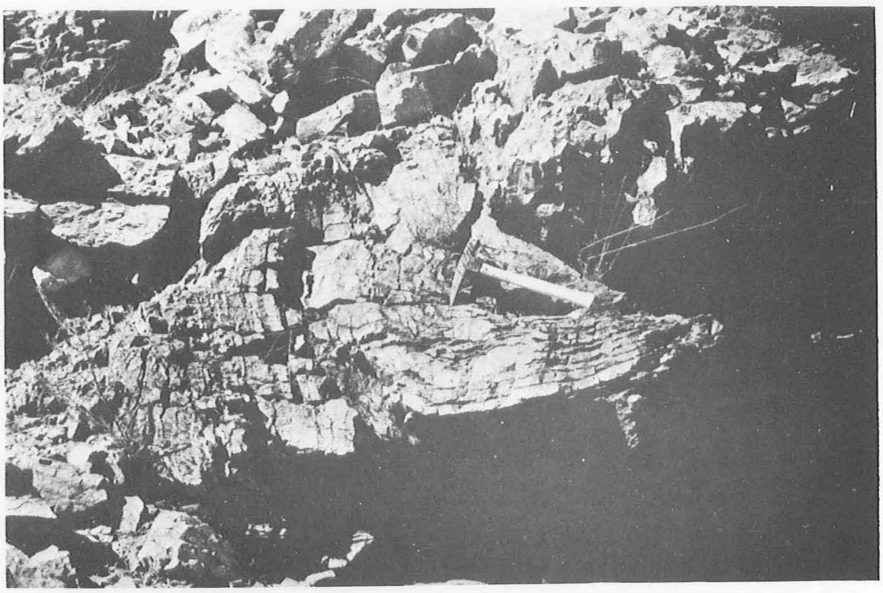
C

Plate 3

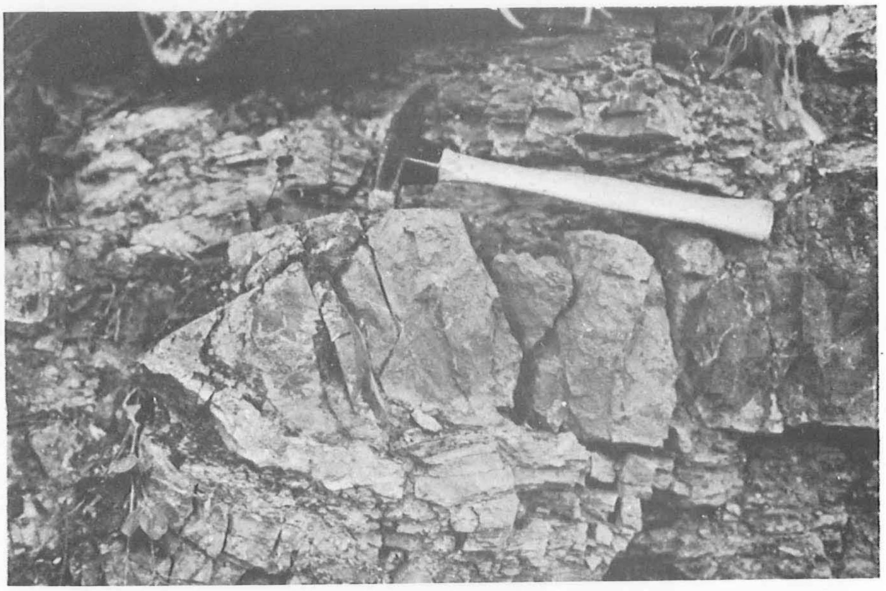
A. Second-phase open folds in the middle Heavitree Quartzite unit of Whisky Boot Hill.

B. Recumbent second-phase folding of the Bitter Springs Formation northwest of Whisky Boot Hill.

C. Chevron folds in the Bitter Springs Formation northwest of Atnarpa Range (second-phase).



A



B

C

<u>Folds, F_3</u>. Since no penetrative F_2 fabric exists, it is impossible in many regions to establish whether a subsequent folding deformation, F_3, has occurred. Thus in many localities an F_3 phase is not distinguished; if it exists it has overprinted the F_1 fabric in a manner similar to the second-phase folds. Evidence that a subsequent F_3 folding phase does exist is provided by:

a) the warping of second-phase fold axes and kinks in the cover rocks north of Atnarpa Range;

b) the coaxial refolding of the F_2 isoclinal folds in the western part of Atnarpa Range to produce a type 3 interference pattern (Ramsay, 1967). An incipient fracture cleavage is axial-plane to the third-phase folds in some localities.

The dispersion in orientation of the F_2 fold axes in both basement and cover rocks (Map 2) does not, in itself, imply subsequent refolding, as will be discussed at the end of this section.

The large approximately east-trending folds that warp the thrust sheets in Atnarpa Range are considered to belong to the third-phase, since there is neither overprinting evidence that indicates a later deformation nor any evidence that they belong to the second-phase deformation. In some localities, where the second-phase folds are not represented, the north-trending L_1 lineation has been folded with the thrust sheets in a near vertical plane about east-trending axes (Map 2). Stereograms for subareas of Atnarpa Range may indicate that the east-trending folds have rotated the L_2 lineation in a small circle (Map 2, subarea 2) suggestive of a parallel fold mechanism; but this is not conclusive. Independent observations of minor fold profiles indicate that they approximate very closely to the true concentric fold model, and the existence of slickensides in the platy unit may indicate that the fold mechanism has been one of flexural slip.

The map pattern for Atnarpa Range (Map 1) shows that F_3 warping of the thrust sheets has resulted in the repetition across strike of the platy quartzite. Furthermore, the distribution of units and the plunge of fold axes is suggestive of a north-trending component of folding, especially in the eastern end of Atnarpa Range, where fold axes plunge steeply northeast. Gentle folds trending north-northeast south of Whisky Boot Hill and open upright folds in the platy quartzite at Atnarpa Range probably all belong to the same macroscopic folding phase that warped the east-trending fold axes of Atnarpa Range. It would be expected that double folding of the basin and dome type would occur owing to the intersection of the axial planes of these two upright F_3 folds. The shape of basins and domes arising from double folding is influenced by the following factors:

a) the relative amplitudes of the folds. It is considered that double folding in Atnarpa Range did not occur because the amplitude of the east-trending folds is greater than that of the gentler north-trending folds;

b) the angle between the fold axes. Where the axes approach each other in orientation an elliptical basin and dome plan results, which, in the limit of axial coincidence, gives way to normal cylindrical folding. Such domes are observed in the Whisky Boot Hill region with their long axes oriented north, and are considered to arise from the interference of north and north-northeast-trending fold axes.

Although the dominant trend of the folds in the southern part of Atnarpa Range is east, the map pattern (Map 1) shows that they have been warped on a macroscopic scale toward the north. The hills and spurs of quartzite in thrust sheet 1 north of Atnarpa Range all demonstrate the macroscopic warping associated with the variably plunging anticlinal fold axes. The time relationships of these three macroscopic components are equivocal since only the tight concentric folds have associated minor folds. Whereas in subareas 4 and 3 east-west folding dominates, farther east in Atnarpa Range (subareas 1 and 2) the stereograms indicate that a fold axis defined by the centre of a small circle of lineations has been warped from east to northeast with its locus of folded lineations, and that this has been accompanied by an increase in plunge from horizontal to some 40° towards the northeast. In subarea 1, three great circles of poles to bedding may indicate greater curvature of the warped fold axes towards the eastern end of Atnarpa Range. The pole to one of these girdles coincides with the centre of a small circle of lineations.

Warping of fold axes may be explained by:

a) reactivation of earlier folds, thereby distorting the youngest axial plane (Ramsay, 1958; Tobisch, 1967). This is unlikely, since earlier folds would be too small to effect the warping required;

b) subsequent warping of variably plunging east-trending folds by non-cylindrical folding. The ellipsoidal double folds make this unlikely;

c) one phase, F_3, of non-cylindrical, non-planar folding (Turner & Weiss, 1963). This is considered most likely.

During this phase, interfering fold systems developed simultaneously and the complex folds can be resolved into three macroscopic components, (Fig. 5e). As deformation proceeded, the east-trending folds probably also tightened (Ramsay, 1963).

Discussion

Facing criteria indicate that all thrust sheets are consistently upright throughout the area except where local isoclinal recumbent folding has inverted the sequence; in all cases it is the thrusting that has caused the large-scale repetition of the succession. This study does not, therefore, support the hypothesis that the White Range represents the inverted synclinal limb of a fold nappe. Rather, it appears that the allochthonous basement is in thrust contact with the Heavitree Quartzite, and the intensification of the F_1 fabric towards the quartzite basement interface tends to support this conclusion. If macroscopic recumbent folding had occurred, it would be expected that a thoroughly penetrative fabric would be developed uniformly at all structural levels. Furthermore, development of mylonitic banding as is observed in both basement and cover is commonly related to major thrusting (Johnson, 1967).

Few examples exist of basement cover interactions in which basement-cored fold nappes have developed in thermal environments as low as greenschist facies grade; invariably the deformation responsible for these fold nappes is associated with high-grade assemblages, as in the Pennine zone of the Alps or the Scandinavian Caledonides (Strand, 1961). When the cover is of shallow depth and the metamorphic grade is low, the basement is usually involved in thrusting and any recumbent folding in the cover occurs as a consequence of the thrusting. Examples of this style of interaction are found in the High Calcareous Alps and in the Shetlands (Flinn, 1958).

Both the increase in intensity of the F_1 fabric near thrust faults and the occurrence of a similar fabric in both allochthonous basement and cover in the northern part of the White Range suggest that the major thrusting episode, in which the basement was emplaced into the cover, was coeval with the F_1 deformation, although some deformation may have preceded thrusting. Deformations later than the F_1 phase have had little or no effect on the F_1 fabric in the northern part of the White Range (Map 2, subarea 6) where poles to foliation (S_1) and lineation (L_1) are arranged according to the S-tectonite pattern with orthorhombic symmetry (Flinn, 1965) defined by the dimensional orientation of strained quartz grains. This subfabric is homotactic with a similar one in the allochthonous basement adjacent to the White Range (Map 2, sheet 3).

Flinn has argued that a direct correlation exists between the XY plane of the strain ellipsoid (where X, Y and Z are the principal axes of the strain ellipsoid and $X \geqslant Y \geqslant Z$) and the foliation. However, this is only valid where it can be shown that there is no rotational or monoclinic component of symmetry in the fabric. It is considered that the first-phase foliation does correspond to the XY plane of the strain ellipsoid since besides the orthorhombic symmetry of the subfabric, strain analysis indicates that the direction of maximum shortening was normal to the foliation. Furthermore, the presence of mylonitic layering is thought to reflect a flattening origin; Johnson (1967) has suggested that the shape of relict grains surrounded by fluxion structures in mylonites is reminiscent of boudinage in which 'pinch and swell' structures result. Khan (1972) has found that the crystallographic subfabric of quartz grains in the quartzite of the range east of Atnarpa homestead is homotactic with the mesoscopic subfabric. It is difficult to understand why a rotational strain component due to simple shear is not observed near thrust contacts. This problem is discussed further on p. 24.

It is impossible to determine for certain whether S_1 and S_{n+1} are true axial-plane foliations since, as mentioned previously, transposition of S_o or S_n may have proceeded to an advanced stage, or the S_1 fabric may have been imposed independently when both basement and cover were deformed. Alternatively, unfolding may have occurred during subsequent deformation (Flinn, 1962). The flattened nature of F_2 isoclinal folds and the existence of boudinage deflecting the S_1 foliation suggest that the flattening may have persisted during the second phase of deformation. Other studies have shown that boudinage may occur when the compression is normal to the layering (Cobbold, Gosgrove, & Summers, 1971). Kink folds may also develop under such circumstances.

The notion that deformation within orogenic belts is episodic has been conspicuous in the literature. However, with the recent revision of concepts in global tectonics it now seems likely that a series of discontinuities in deformation during orogenesis is the exception rather than the rule. The use of phases F_1, F_2, and F_3 in this Record is not meant to connote an episodic deformation nor even that all structures of each phase formed synchronously; the terms are convenient to indicate merely that a broad time sequence of deformation can be recognized within the area. Furthermore, owing to the lack of continuous outcrop, it is impossible to correlate folds of the same 'phase' from one area to another since displacement in time of the separate deformational sequences cannot be precluded. This situation arises in progressive deformation because it is impossible to characterize any one phase in time or space. Park (1969) has argued that fold style, orientation, and symmetry are of no value in correlating folds from one area to another, and

Williams (1971) has shown that the same fold styles and orientations may recur in subsequent phases. Five styles of folding are assigned to the F_2 phase since all refold the F_1 fabric and are locally disrupted by third-phase structures. Box folds and kinks have formed in the limbs of F_2 isoclinal folds, and the variation in profile suggests that all gradations between concentric and conjugate folds occur. Such close associations of different styles have been investigated by Cobbold, Cosgrove, & Summers (1971), who note that during compression nearly parallel to the foliation, either sinusoidal or box folds develop according to the degree of anisotropy of the rock. They suggest that the degree of anisotropy rather than other rheological properties controls the style of developing folds and that a series exists between concentric styles developed in weakly anistropic rocks and conjugate-kink styles developed in rocks of strong anisotropy. These results appear to be relevant in areas of second-phase deformation; whereas isoclinal, conjugate, and box folds are restricted to the platy quartzite or to well foliated rock, the more open, flattened concentric folds are developed only in the thickly bedded Heavitree Quartzite farther south.

The great variation in orientation of F_2 fold axes indicates in a striking fashion that orientation is of no value in characterizing the folds of a particular phase. In the vicinity of subarea 4 of thrust sheet 1 the F_2 axes trend from south to east, whereas in the southern part of the White Range they vary from north-northeast to east (Map 2, subareas 5 and 4). The variation in plunge observed for all azimuths may be due to a heterogeneous strain during F_2 deformation or to later folding. During the non-cylindrical, F_3, phase of deformation the variable fold axes would intersect F_2 fold axes of initially constant orientation, warping them into their present orientations. An alternative explanation involves the dispersal of the F_2 fold axes by progressive deformation (Flinn, 1962) before F_3 folding. In this case, if the XY plane of the finite-strain ellipsoid was oriented to the east, increments of infinitesimal strain may be represented by folds as the surface of no infinitesimal longitudinal strain rotated eastward. Subsequent F_3 folding locally warped and disrupted the axes of the variably oriented F_2 folds.

DYNAMIC METAMORPHISM AND STRAIN IN THE BASEMENT AND COVER

During the first and possibly the second deformation associated with nappe emplacement, basement and cover underwent strain-induced textural changes and metamorphism to greenschist facies grade. The metamorphism was progressive in the cover but retrogressed the amphibolite assemblages of the basement. In the Atnarpa Range region of the nappe complex, equilibrium was not attained in the rocks of the allochthonous basement. Assemblages representative of the amphibolite grade of regional metamorphism persist, although towards thrusts and farther north, an increasing degree of recrystallization accompanies cataclasis in both basement and cover. North of the White Range, cataclasis is subordinate to recrystallization and the serial change in the degree of cataclasis northward is paralleled by an increase in the amount of plastic strain. Higgin's (1971) classification of mylonites is used for the deformed rocks of the basement and cover.

Basement Rocks

All basement rocks possess a foliation or mylonitic layering near thrust contacts. Ellipsoidal relics of microcline up to 2 mm in size are oriented parallel to the foliation, and become extremely flattened near thrust contacts. Alternating sericitic and quartzo-feldspathic layers of approximately equal thickness envelop the feldspar augen, which are extensively seriticized and are accompanied by aggregates of recrystallized grains of quartz and feldspar in the 'shadow region' at the apices of the augen. Deformation twins and tension cracks oriented at a high angle to the foliation are present in the augen in contrast to the new, strain-free granules of the coarse layers. Grain boundaries in the quartzo-feldspathic bands are either cuspate or straight. Close to thrusts and farther north feldspar relics are rarer and give way to layers of finer-grained feldspar in which triple points are common and the effects of strain minimal. In some localities the recrystallized grains have also been strained as evidenced by their elongation parallel to the foliation, S_{n+1}, and by the presence of undulose extinction. In the region east of the White Range quartzo-feldspathic layers with two distinct grainsizes are present, due to the recrystallization of the older strained layers to smaller, strain-free grains. This process reaches a limit northeast of the White Range near the thrust contact, where recrystallization predominated over cataclasis, and the rocks are mylonites with only a few relics surviving. Fluxion structure corresponding to the S_{n+1} foliation is still apparent in these rocks.

In the south near Atnarpa Range and away from the thrust contacts, cataclasis is the dominant process, although the plagioclase has been partly altered to epidote and the biotite chloritized. Miocrocline crystals are common and have been kinked or fractured. Strain-free coarse crystals surround some relict feldspars in layers parallel to the foliation.

Cover Rocks

In the eastern part of Atnarpa Range the Heavitree Quartzite has been only weakly metamorphosed. Grains are still quite rounded, although slight strain is indicated by the presence of undulose extinction. The loosely cemented gritty unit contains minor amounts of sericite which completely envelop the clasts. Farther west in Atnarpa Range, limited recrystallization within the gritty unit has resulted in aggregates of medium-grained quartz, and the rocks are protomylonites. Near thrust contacts in Atnarpa Range recrystallization is minimal and the rocks are cataclasites.

Northwest of Atnarpa Range polygonization of strained quartz grains has resulted in a mosaic of strain-free subgrains which preserve the form of the host quartz. Straight to slightly arcuate boundaries and triple-points characterize the new grains, which together with the relict crystals form a mortar texture. In other localities on the northwestern flank of Atnarpa Range little recrystallization has occurred and quartz grains have been considerably elongated. On Diomedes Hill the mylonitic fabric has been preferentially developed in the basal arkose of the Heavitree Quartzite.

In the region of Whisky Boot Hill and other localities south of the White Range, mylonites contain relict quartz fragments that have been elongated by 'necking' parallel to the foliation S_1. Both matrix and relics are strained, and the grains of the recrystallized layers have been elongated parallel to the foliation. This suggests that periods of cataclasis and recrystallization may have alternated.

The Heavitree Quartzite of the northern half of the White Range exhibits all stages of comminution to a fine-grained aggregate. The proportion of relict grains to recrystallized matrix is small and the quartzite possesses a weak fluxion structure; the rocks are blastomylonites. Relict grains up to 1.5 mm in diameter are generally cracked and have undulose extinction, although some have been polygonized to a mosaic of subgrains with straight boundaries. Generally, the relics have been flattened in a plane parallel to the foliation. Extensive recrystallization has rendered strain analysis impossible in the northern part of the White Range.

In the shales of the Bitter Springs Formation, metamorphism has led to a differentiation of sericitic and quartzo-feldspathic layers although some large feldspar fragments persist as relics. The quartz of the coarser layers is polygonized and the micaceous layers are in places plicated.

STRAIN ANALYSIS

The shape and orientation of pebbles and grains in a deformed rock are determined by:

a) the composition of the grains and pebbles;

b) the ductility contrast between particles and matrix;

c) volume change during deformation;

d) the original shape and fabric of the rock prior to deformation;

e) the finite strain sustained by the rock.

Strain measurements have been confined to the Heavitree Quartzite, in which the pebbles of the basal conglomerate are predominantly quartzitic and all the grains are composed of quartz.

It has been predicted that when viscous deformation of a medium occurs, less ductile particles will experience a torque tending to align the long axes of the particle normal to the flow direction (Jeffrey, 1922; Gay, 1968). Clearly, this effect would have considerable influence on the shape and orientation of the particles after deformation. Because of the high shear-strain necessary in rocks to achieve this rotation, Ramsay (1967) considers the effect negligible.

If a volume change occurs during deformation the observed apparent strain will differ from the true strain. The relatively undeformed quartzite of Atnarpa Range is well sorted and cemented; any change in volume is likely to be of only minor significance.

Since the constituents of the rocks before deformation were not perfectly spherical, the final shape of the particles does not reflect the true, finite strain in the rock. This is especially true of pebbles in deformed conglomerates, which invariably have initially ellipsoidal shapes and a primary fabric. Mature orthoquartzites are likely to be less critical, as the grains are generally well rounded. In this analysis the primary shape and fabric factors have been taken into account by using a method suggested by Ramsay (1967) and developed by Dunnet (1969). Dunnet derived expressions relating the final ratio of the axial lengths of a particle to its initial magnitude and orientation assuming that it deformed homogeneously with its matrix and approximated an ellipsoid during deformation. From these he constructed curves which could be readily used to separate the initial and strain components of the shape. For any two orthogonal sections, measurements of the long and short axes of the particles are recorded on a 'scatter-diagram' in which the final length ratios, $\sqrt{R_f}$, are plotted against the orientation of the particle, referred to an arbitrary azimuth. For an initially random fabric the points fall symmetrically inside a shield-shaped field and the intersections of the enveloping curve on the ordinate permit direct calculation of the initial ratio, $\sqrt{R_o}$, and strain ratio, $\sqrt{R_t}$, since:

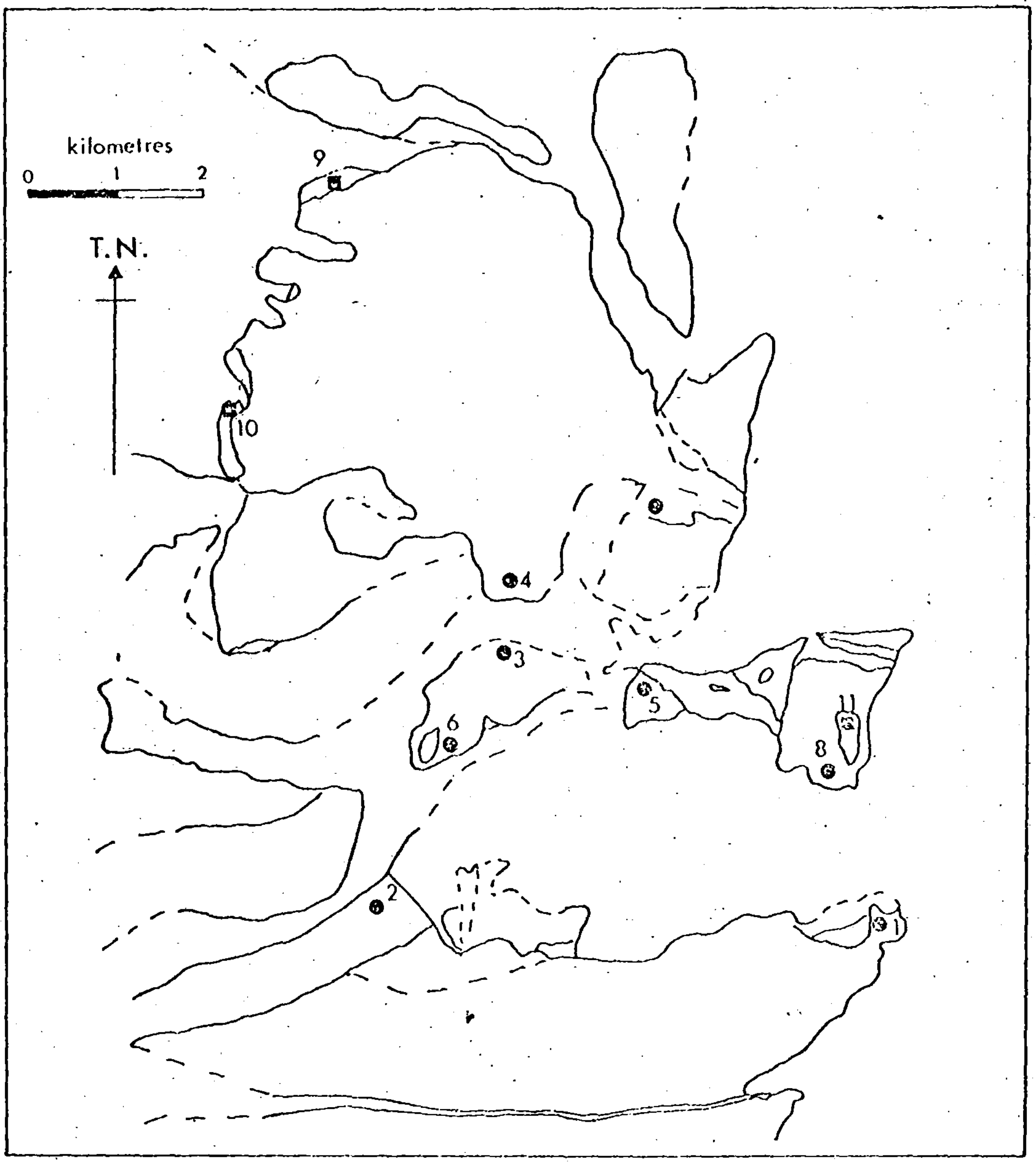


Figure 9

Localities for which strain measurements were made. The corresponding strain plots are shown in Figures 9, 10, and 11.

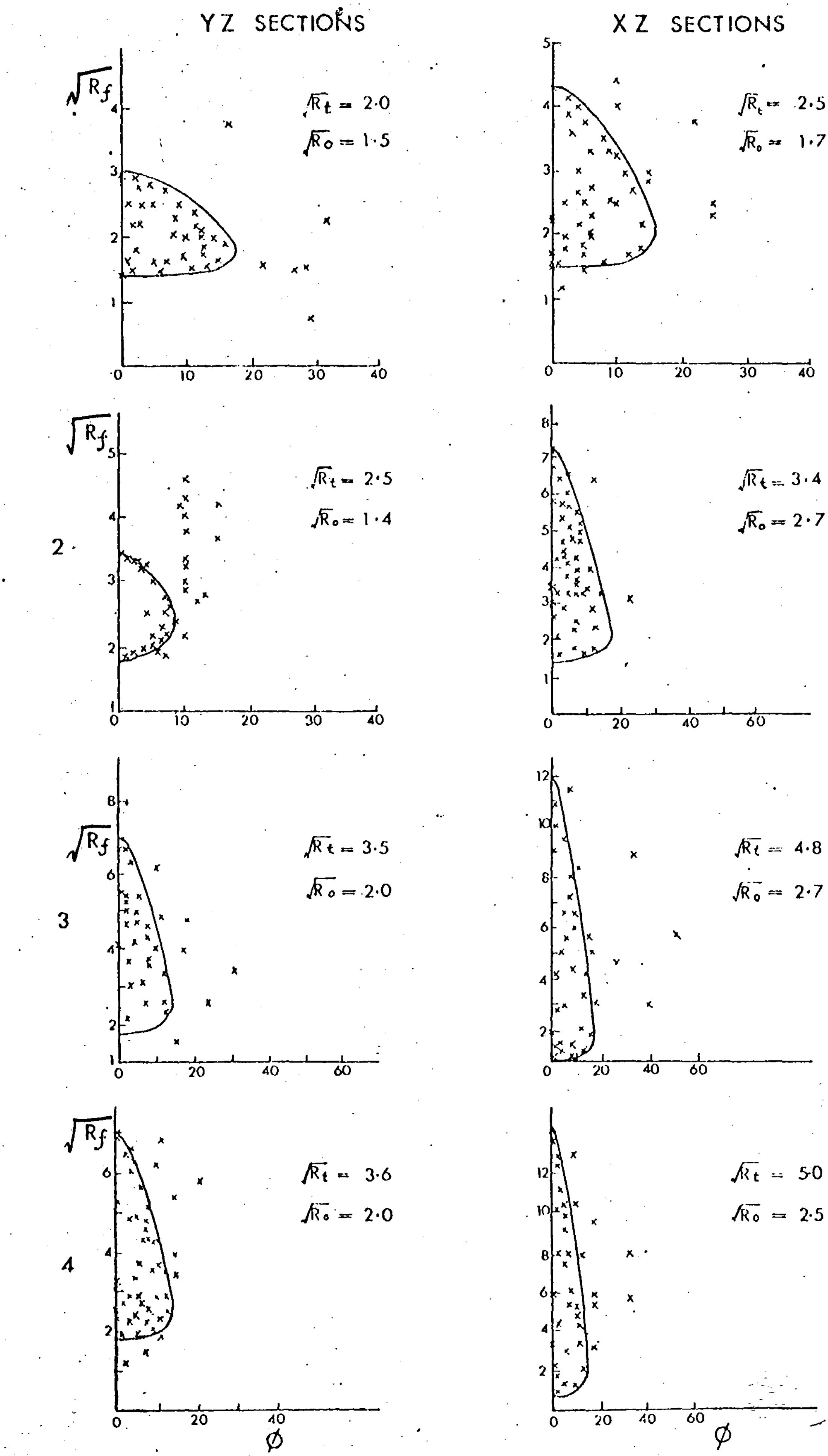


Figure 10

Scatter-diagrams for localities 1, 2, 3, and 4 in the gritty and massive Heavitree Quartzite.

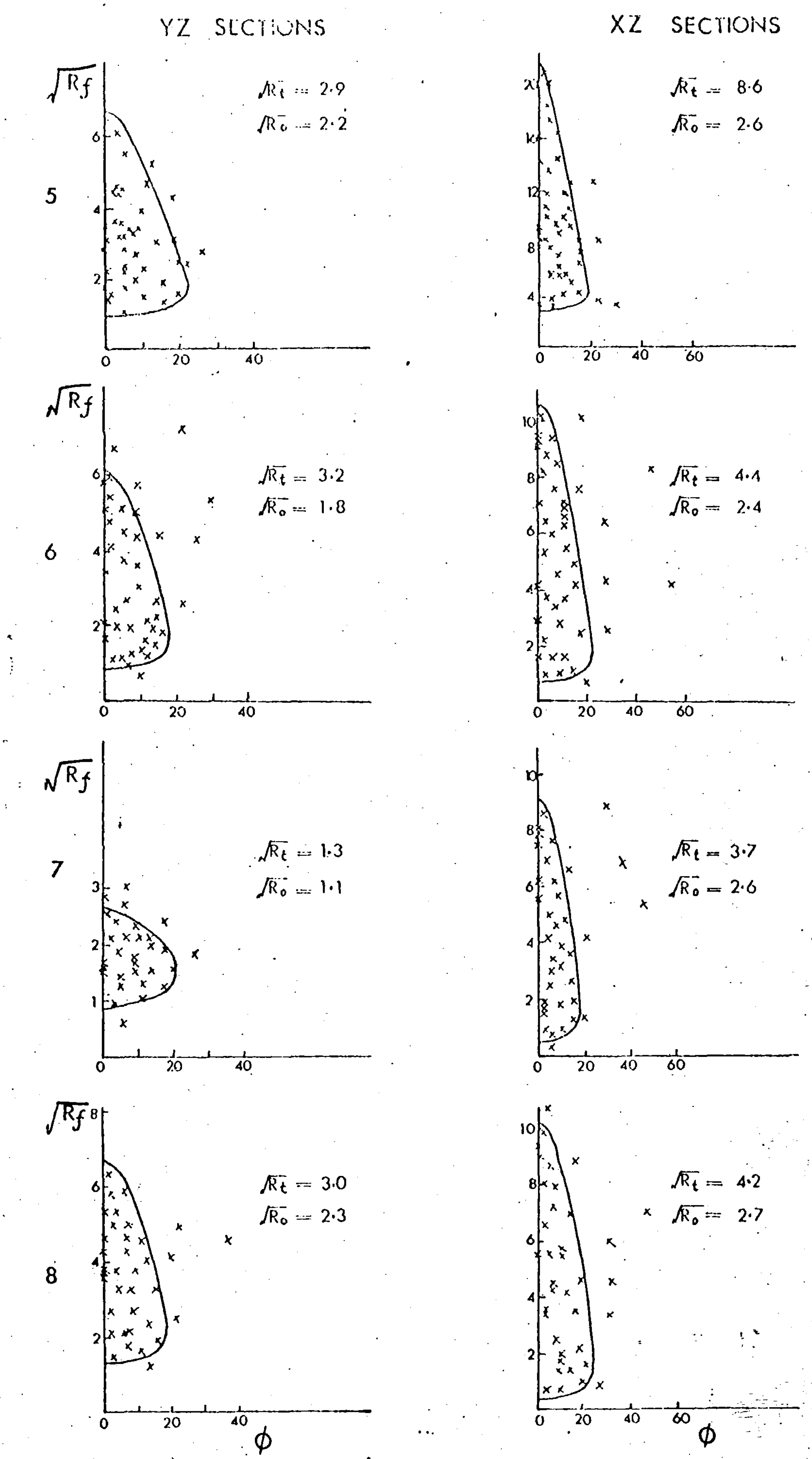


Figure 11

Scatter-diagrams for localities 5, 6, 7, and 8 in the massive Heavitree Quartzite.

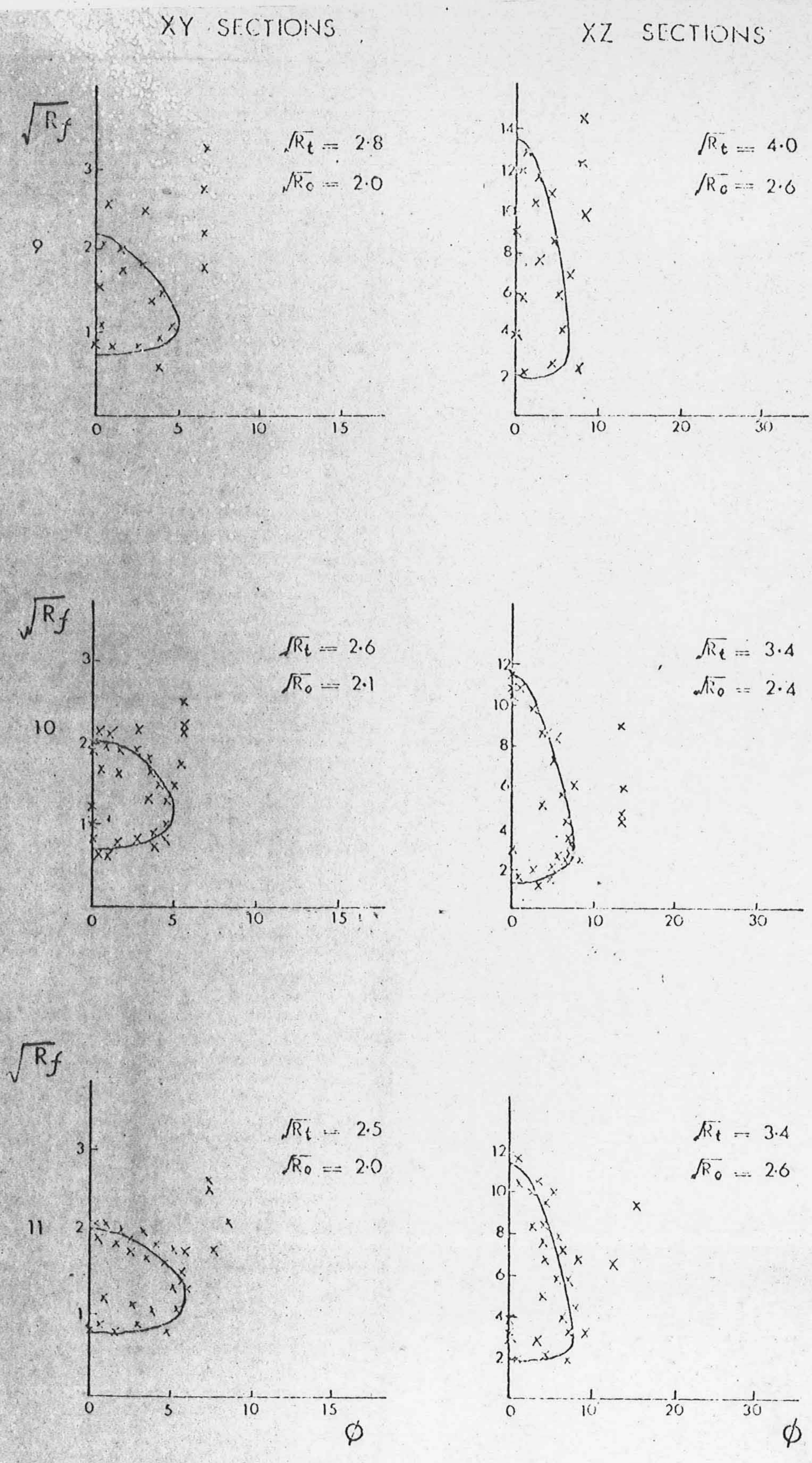


Figure 12

Scatter-diagrams for pebbles in the basal conglomerate at localities 9, 10, and 11.

$$(R_f)\ max = R_t R_o \quad (1)$$

$$(R_f)\ min = R_t / R_o \quad (2)$$

Dunnet's procedure has been followed in this study.

Method

Specimens of Heavitree Quartzite were obtained from eight localities within the Arltunga area (Fig. 9). Measurements could not be made on rocks from the northern part of the White Range because of the extensive recrystallization. Specimens from the gritty quartzite were ideal for analysis since the primary quartz overgrowths could still be recognized, and thus it was possible to ensure that a single original grain was being measured. In other specimens care had to be taken that a measured grain had not been necked or sheared into subgrains. For each specimen two thin sections were cut, one of which was parallel to the lineation and both normal to the foliation, thus representing the XZ and YZ planes of the corresponding strain ellipsoid. For each section an arbitrary azimuth was selected and the orientations of the grains measured relative to this. Using a graduated ocular, the long and short axes of each grain were measured and recorded. Generally, thirty to forty readings were taken for each section.

This method was modified to compute the strain within the pebbles of the basal conglomerate at localities 9, 10, and 11 (Fig. 9). Reference azimuths were established in the field on two approximately orthogonal surfaces in the conglomerate. Dunnet's procedure was repeated, measuring the pitch of each axis relative to the reference line and scatter-diagrams plotted for each locality. An advantage of this method is that the measured surfaces do not have to be principal sections. Gay (1969) has employed a similar technique for measuring deformed conglomerates.

Scatter-diagrams (R_f - $\emptyset$) for all localities are plotted in Figures 10, 11, and 12. By using the theoretical curves combined with the R_t, R_o values calculated from equations (1) and (2), the best fitting curve was found for each distribution. Ratios of the principal axes of the strain ellipsoid ($\sqrt{R_t}$) have been determined for each principal section; the ratio of the axes corresponding to the XY principal section is calculated from:

$$\sqrt{R_{txy}} = \sqrt{R_{txz}} / \sqrt{R_{tyz}}$$

Finally, a Flinn deformation diagram (Flinn, 1962) was plotted for each locality to determine the change in type and magnitude of strain in the area (Fig. 13). A parameter, k, is often used to describe the shape of the strain ellipsoid; it represents the slope of the straight line joining the plot of the ellipsoid and point (1, 1):

$$k = a-1/b-1$$

where $a = X/Y$ and $b = Y/Z$

Results and Discussion

The values of the initial length ratios, $\sqrt{R_o}$, for all principal sections in the middle Heavitree unit generally lie between 1.0 and 2.5 and reflect the primary shape of the particles. The undeformed ellipsoid calculated from the $\sqrt{R_o}$ values for the basal conglomerate has an average k value of 0.85, indicating that the initial pebbles were triaxial. The scatter-diagrams for the middle Heavitree unit suggest that in most localities the initial fabric was nearly random, although an initial fabric is likely to have been present at locality 2 since there are few points within the curve and a concentration along a particular azimuth. An initial fabric is also apparent within the basal conglomerate, as may be expected. Weak fabrics may have existed at other localities, explaining the points distant from the main distribution. However, these discrepancies could also result from errors of measurement.

Most localities have a strain ellipsoid in the flattening field ($1 \geqslant k \geqslant 0$) although the ellipsoids for the conglomerates and for locality 7 plot within the field of constrictional strain ($\infty \geqslant k \geqslant 1$). It is also apparent that the average strain increases progressively northward, reaching a maximum in the southern part of the White Range (Fig. 13) before the grains begin to recrystallize. A straight line with a k value of 0.18 can be fitted through the ellipsoids in the flattening field and may represent a deformation path (Flinn, 1962; Ramsay, 1967). Flinn has suggested that the deformation paths for viscous and plastic irrotational deformation are straight lines; the straight line best fitting the ellipsoids in Figure 13 may reflect irrotational plastic deformation, departure from the line being explained by experimental errors. Alternatively, a small component of rotational strain may be present. Strain within the conglomerate is highest in the northernmost locality and has an average k value of 2.45.

A progressive increase in intensity of dynamic metamorphism northward is paralleled by an increase in irrotational flattening and plastic strain which may represent a deformation path for the region.

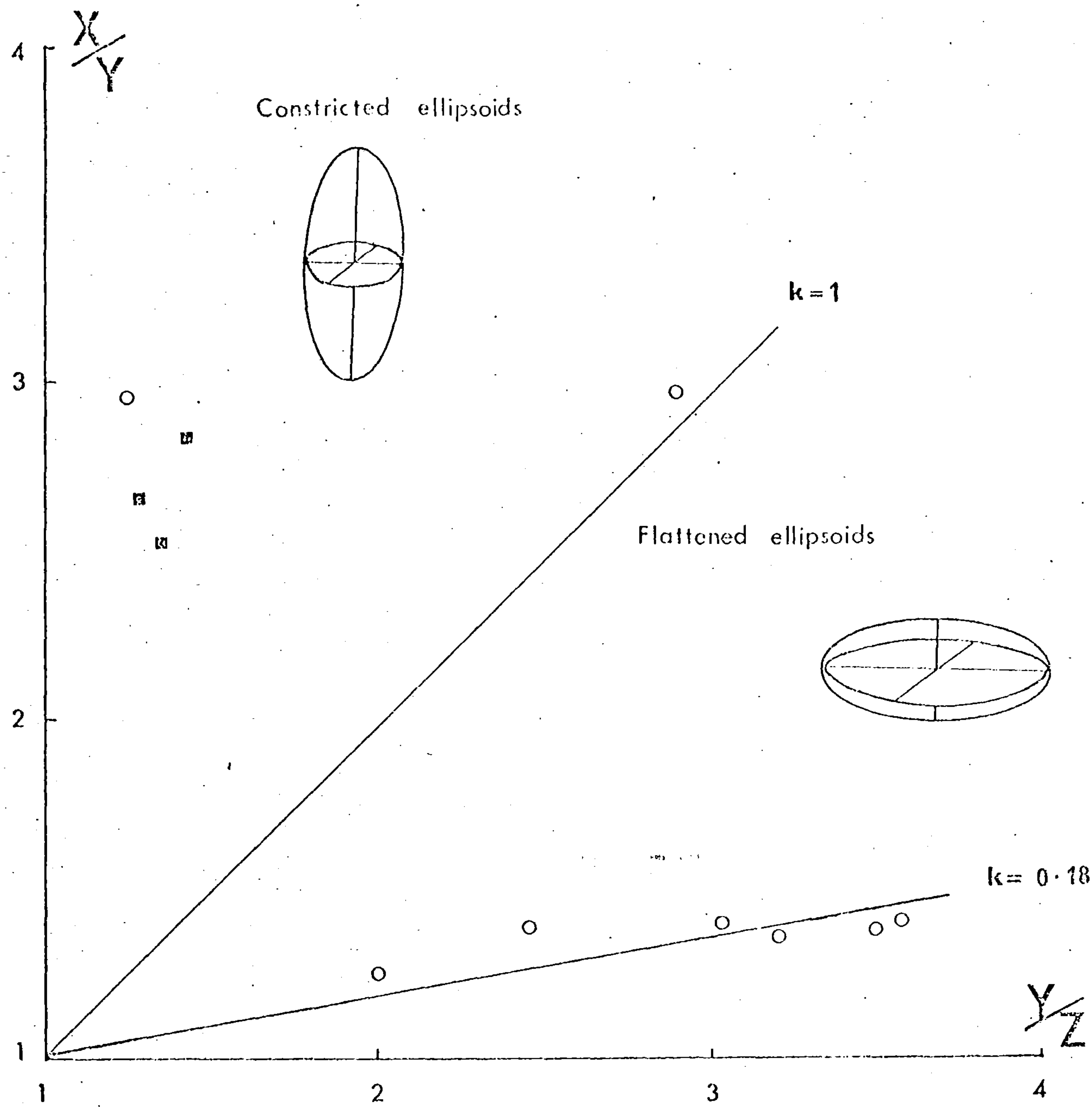


Figure 13

Deformation plot for all localities (after Flinn, 1962). X, Y, and Z are the lengths of the principal axes of the strain ellipsoid (X ⩾ Y ⩾ Z).

Open circles: the massive and gritty quartzites.

Squares: pebbles of the basal conglomerate.

SUMMARY OF RESULTS AND HISTORY OF DEFORMATION

Summary of Results

The earliest deformation of both basement and cover in the Arltunga area imposed a penetrative fabric and resulted in the introduction of a wedge of basement into its cover of Heavitree Quartzite and Bitter Springs Formation, thereby disrupting the normal stratigraphic succession. This particular style of interaction was apparently controlled by the contrasting rheology of basement and cover and by the anisotropy of the units within the cover, which provided horizons of décollement. Watson (1967) considers that basement and cover are most likely to behave differently during the early stages of reactivation when the two units have contrasting properties. Thrusting also occurred at two other levels in the Heavitree Quartzite. It is clear that the repetition of the cover sequence has been caused by thrusting since:

a) all thrust sheets face upwards; there is no evidence of widespread inversion of the succession;

b) the first-phase fabric is enhanced towards thrust contacts;

c) the development of mylonitic layering is usually ascribed to major thrusting;

d) the low grade of metamorphism is more consistent with thrusting than with the development of major fold nappes.

The first-phase fabric developed concomitantly with thrusting, as evidenced by its enhancement towards thrusts, but may also have been present before the major thrusting. Whether the basement wedge was reactivated along a pre-existing fabric weakness is indeterminable, but it is clear that the present foliations in both basement and cover were coeval, as retrogressive mineral assemblages are associated with the metamorphic segregation. Different styles of the first-phase fabric are considered to be due to the varying responses of different rock types to the same flattening deformation.

Anisotropy within the cover also controlled the development and style of the second-phase folds which refold the first-phase fabric. During this phase four styles of folds developed with various orientations, and field relationships show the close association of isoclinal, box, and conjugate-kink folds. These observations emphasize the difficulties involved in correlating folds from one area to another. Most second-phase folds verge toward the south, and this phase may have been continuous with the first, both occurring during a protracted episode of thrusting.

Flattening strain predominates in the Heavitree Quartzite, although there are also localities of constrictional strain. Both types increase progressively northward, as does the intensity of dynamic metamorphism, and the finite strain must be the result of the combined first and second-phase deformations; it is likely that the initial flattening strain was augmented during the second phase. The occurrence of both constrictional and flattening strains suggests that inhomogeneous strain was associated with the first and second-phase deformations and together with the later F_3 deformation may account for the warping of F_2 fold axes and axial planes. The probable existence of a deformation path during plastic irrotational strain for localities situated progressively northward may indicate that recrystallization north of the White Range was the final result of increasing deformation.

In the southern part of the area the existence of third-phase folds is evidenced by the coaxial refolding of second-phase isoclinal folds. The third phase was a noncylindrical, non-planar phase that warped the thrust sheets and produced double folding in the region of Whisky Boot Hill.

History of Deformation

The probable sequence of events in the Arltunga area was:

1) In late Devonian or early Carboniferous time a wedge of basement was driven up into the cover in response to a horizontal compression acting on both basement and cover (Fig. 14a). The cover was able to deform inhomogeneously; the homogeneous basement, in contrast, was constrained to brittle dislocation. The basement wedge extended at least into the base of the Bitter Springs Formation, where it may have moved along a glide horizon. Above this horizon the sediments of the cover deformed independently under the influence of the allochthonous basement, and were folded into a series of open folds commonly associated with thrust faults. Thrusting was from north to south, as indicated by the vergence of folds and the northward increase in metamorphism and strain.

Sutton & Watson (1962) have invoked a similar explanation for the intercalation of Lewisian and Moine gneiss of Central Ross-shire. A basement slab, the Scardroy sheet, is envisaged as having pierced the Moine sediments which now occur structurally above and below the sheet and everywhere face upward. A similar explanation appears to hold for the basement deformation in the northeastern region of the Greenland Caledonides (Haller, 1971).

2) The direction of maximum shortening (ε_3) became vertically oriented owing to the weight of the basement wedge (Fig. 14b). Stewart (1971) and Khan (1972) have shown that the maximum principal stress was vertical in this part of the

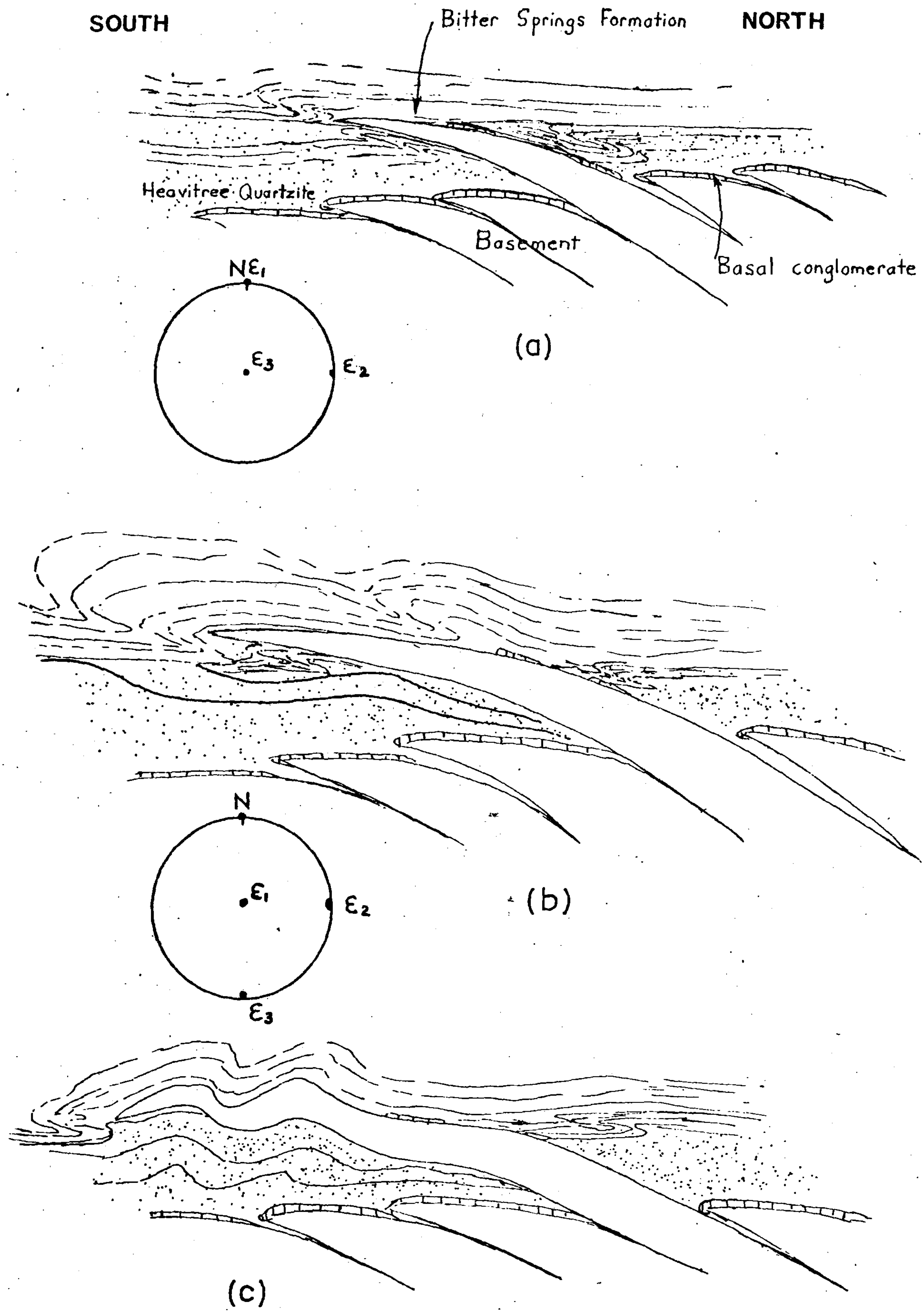


Figure 14

Schematic interpretation of the stages in the structural evolution of the Arltunga region showing the orientations of the corresponding mean-strain axes nappe complex. Although simple shear occurred at the level of the dislocations, the orthorhombic fabric near thrust zones can only be indirectly ascribed to the thrusting; it is the result of the weight and squeezing effect of the overburden. The cover rocks probably contained connate water and, with a rise in temperature corresponding to greenschist metamorphism, were able to flow plastically under the flattening influence of the nappe. In most localities there was a uniform lateral constraint, and so the cover rocks below the basement wedge could only flatten. However, there was also a tendency for plastic flow in a direction of relief southward causing 'neck ng' of pebbles and imposing a mineral elongation. The cover rocks farther north experienced a longer period of strain, as they were closer to the root zone, and eventually started to recrystallize. Rocks farther south, in the vicinity of the Atnarpa Range, sustained a shorter period of strain, and since the metamorphism due to dislocation was weakest in the south, only limited cataclasis occurred.

Lineations parallel to the direction of tectonic transport have been described from many regions, including the Moine Thrust of Scotland (Christie, 1963) and the Taconic Range in eastern U.S.A. (Balk, 1952). These interpretations have been the subject of much controversy. Kvale (1953) has claimed that such lineations are analagous to slickensides, whereas Johnson (1957) suggests the lineations are due to lateral constriction during thrusting. In the Arltunga area the constriction was probably caused by the combined effects of the 'squeezing out' of the cover and a uniform lateral confining pressure in all directions except north-south.

3) Farther southward translation of basement and cover was impeded by the cover rocks squeezed out by the nappe. Thus the attitude of the lateral constraints altered so that the XY plane of the finite-strain ellipsoid was oriented east (Fig. 14b & c). This resulted in a progressive phase of folding (F_2), the axes changing with time towards an east-trending orientation and overprinting the first-phase fabric. Anisotropy controlled the development and style of folds, but in the massive quartzite folding was impossible and two imbricate thrusts developed, finding decollement horizons in the basal Bitter Springs Formation and the gritty unit of the massive quartzite.

4) Emplacement of the basement slab was completed and a macroscopic phase of non-planar, non-cylindrical folding (F_3) warped the thrust sheets and all previous structures alike (Fig. 14c).

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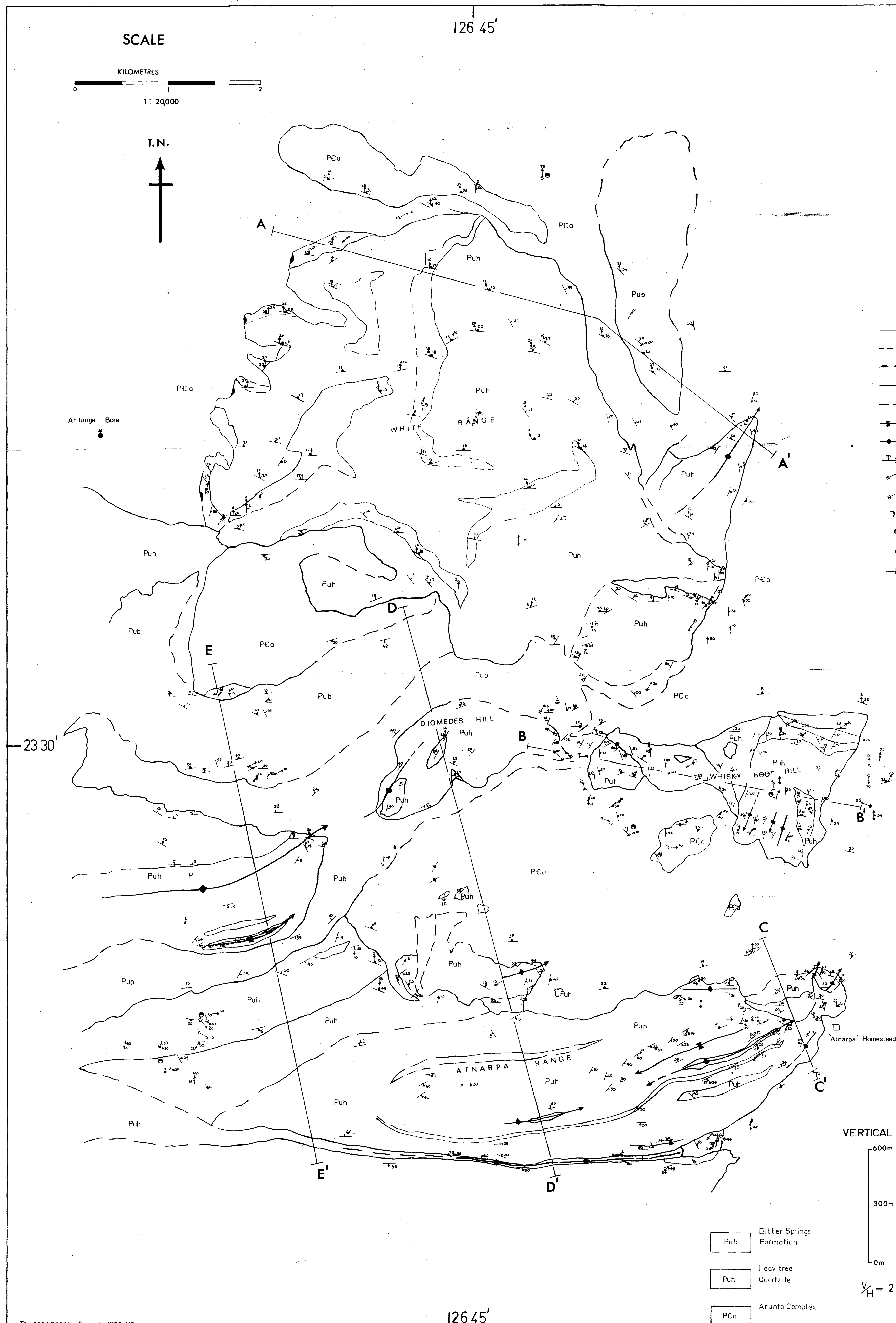
GEOLOGY OF THE ARLTUNGA AREA
CENTRAL AUSTRALIA
MAP 1 STRUCTURAL GEOLOGY



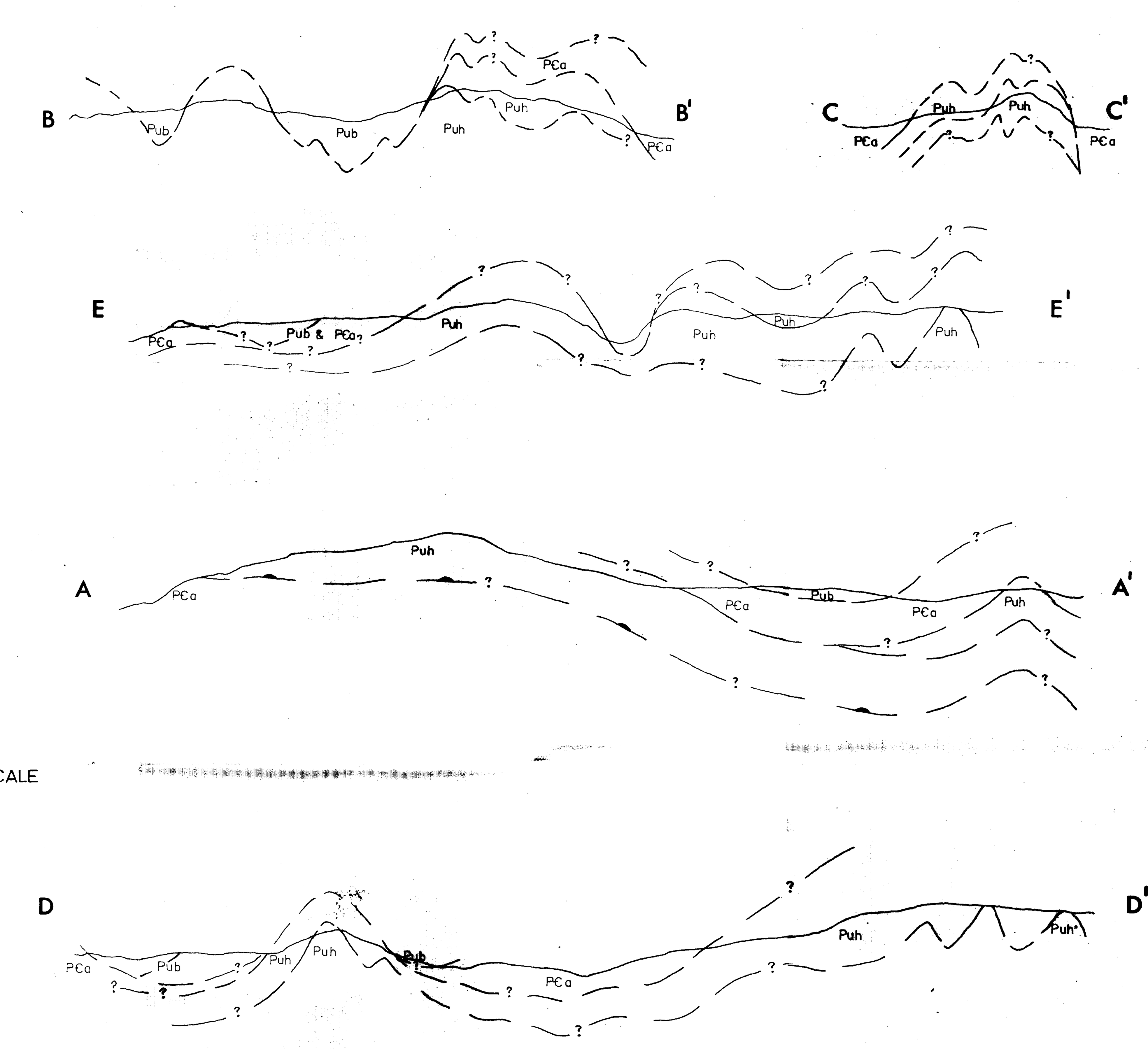
SYMBOLS

- Geological boundary, accurate
- Geological boundary, approximate
- Unconformity, top towards younger rocks
- Fault, position accurate
- Fault, position approximate
- Syncline showing plunge
- Anticline showing plunge
- Fold showing strike & dip of axial plane, plunge of axis
- Plunge of fold showing 'S' vergence
- Plunge of fold showing 'Z' vergence
- Plunge of folds showing 'M' vergence
- Locality of superposed folds
- Strike and dip of bedding
- Strike and dip of overturned bedding
- Strike of vertical bedding
- Strike and dip of upright bedding
- Strike and dip of bedding with plunge of lineation
- Strike and dip of foliation
- Strike of vertical foliation
- Strike and dip of foliation with plunge of lineation

LINEATIONS (trend and plunge)

- Mineral elongation
- Striping
- Long axes of pebbles
- Crenulation
- Slickensides
- Quartz rodding
- Bedding cleavage intersection

CROSS SECTIONS



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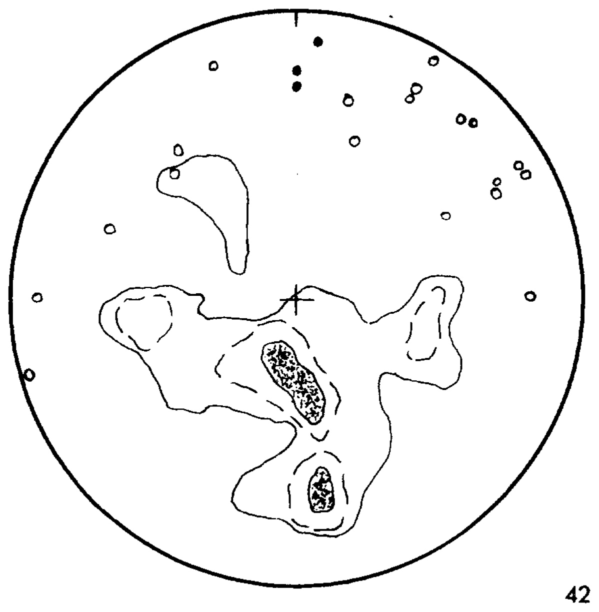
MAP 2

MACROSCOPIC GEOMETRY

THRUST SHEET	SYNOPTIC DIAGRAMS

BITTER SPRINGS FORMATION



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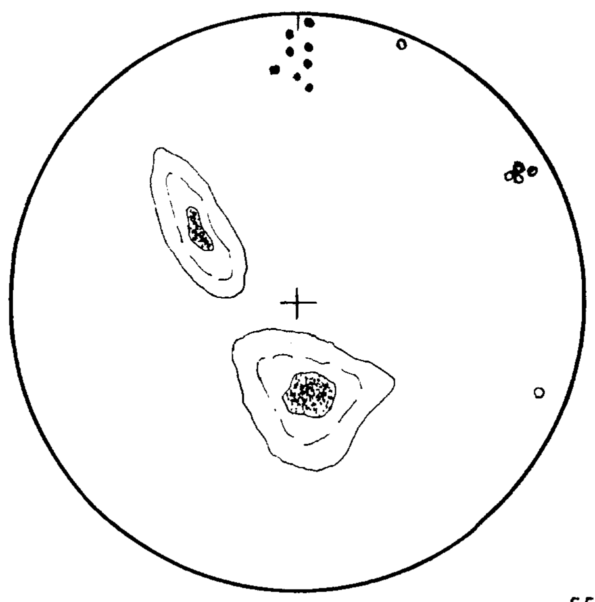

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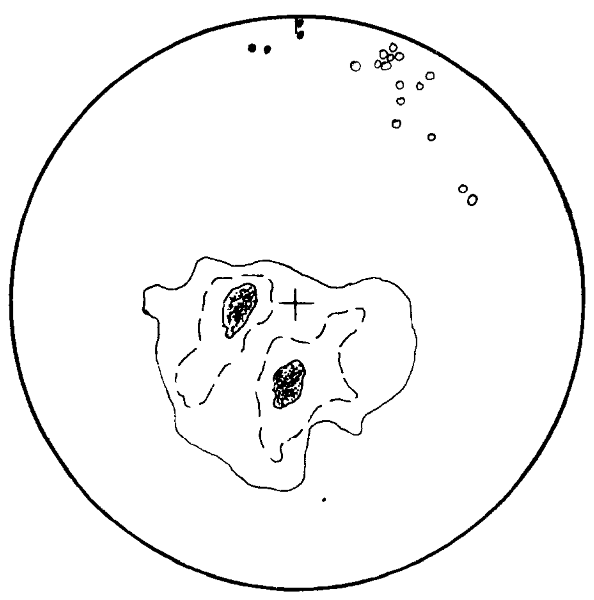

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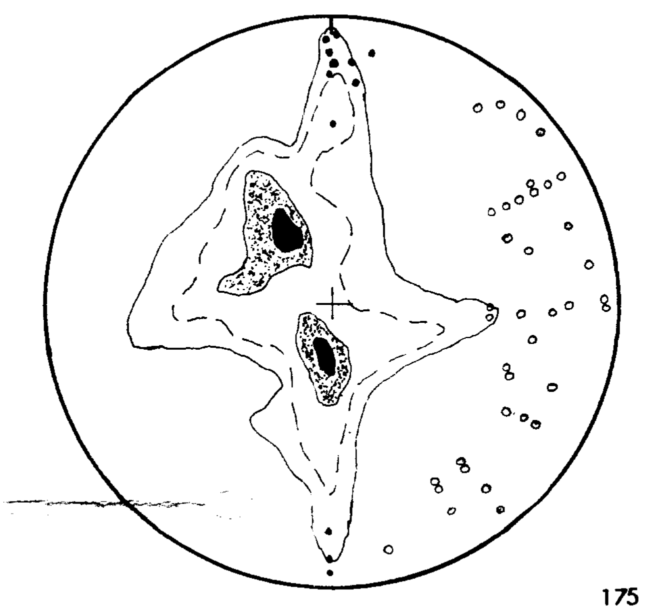

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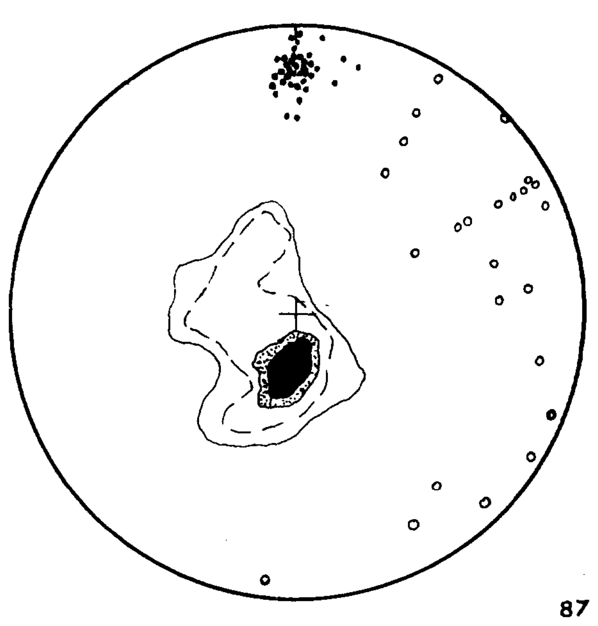
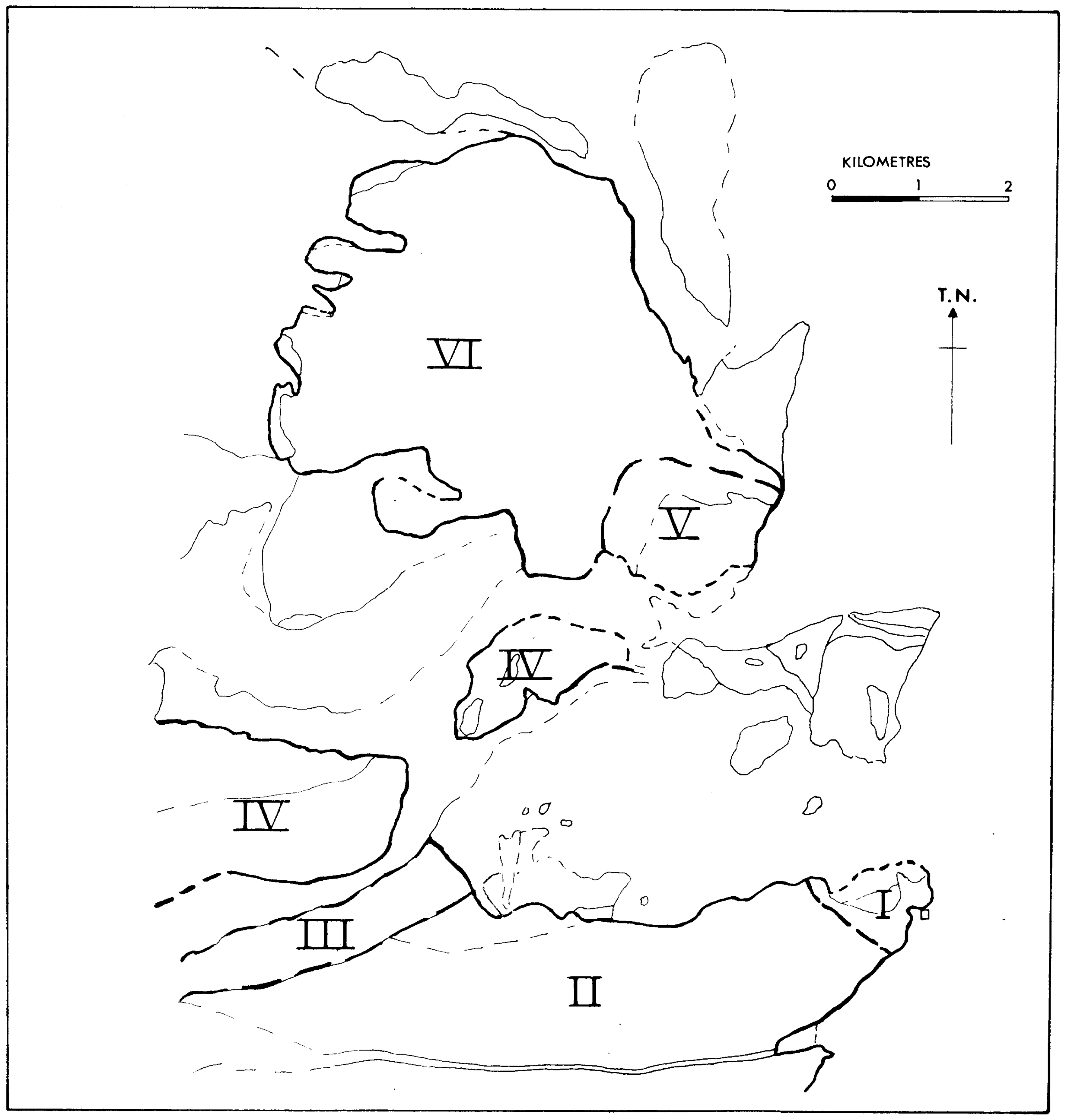




SUB — AREAS

POLES TO BEDDING S_0 — x

POLES TO FOLIATION S_1 — ▲

LINEATION L_1 — ●

LINEATION L_2 & FOLD AXES B_2 — o

Both S_0 and S_1 are incorporated in the synoptic diagrams

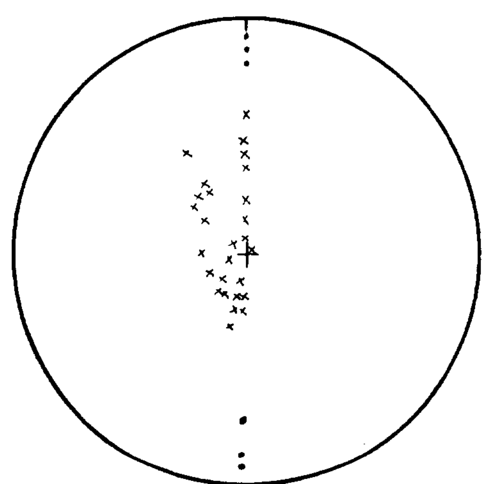
CONTOURS (per 1% area)

1%

5%

10%

20%



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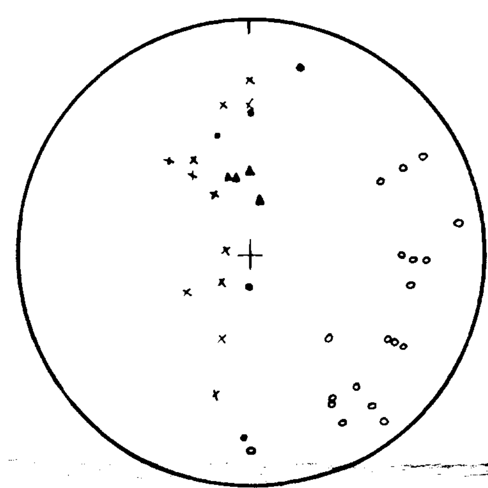

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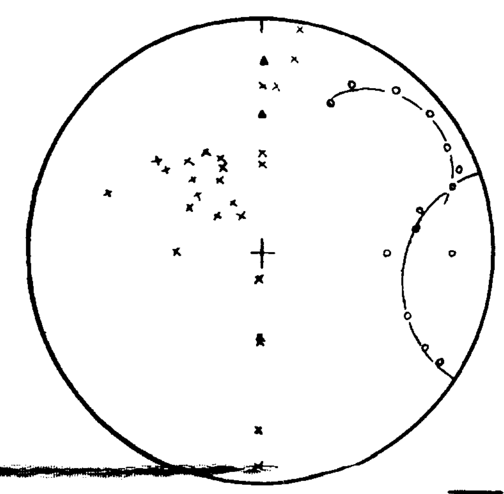

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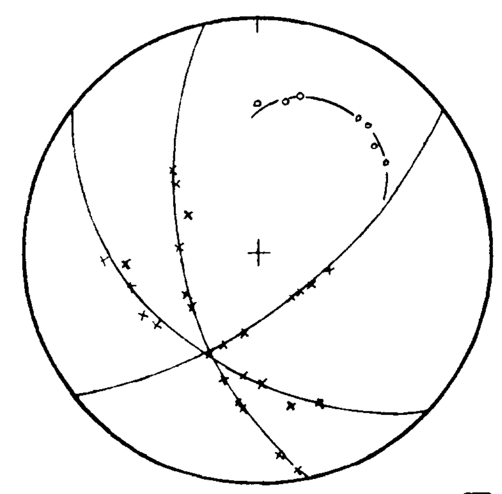

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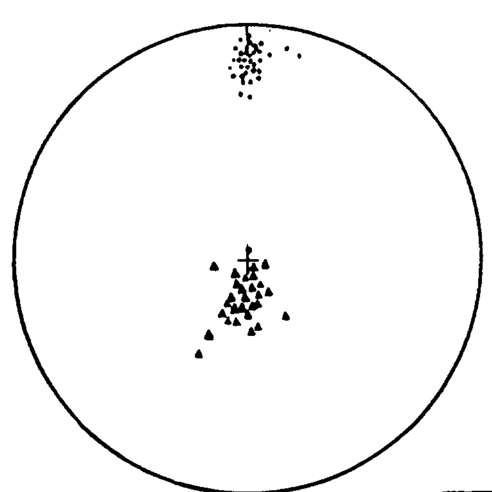

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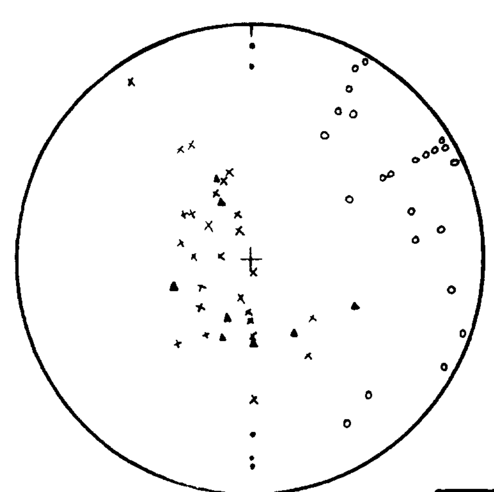

V

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