ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

STRUCTURAL ELEMENTS OF ARCHAEAN GRANITE-GREENSTONE TERRANES AS EXEMPLIFIED BY THE BARBERTON MOUNTAIN LAND, SOUTHERN AFRICA

by

C.R. ANHAEUSSER

INFORMATION CIRCULAR NO. 162

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

STRUCTURAL ELEMENTS OF ARCHAEAN GRANITE-GREENSTONE TERRANES AS EXEMPLIFIED BY THE BARBERTON MOUNTAIN LAND, SOUTHERN AFRICA

by

C.R. ANHAEUSSER

(Deputy Director, Economic Geology Research Unit)

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR NO. 162

September, 1983

STRUCTURAL ELEMENTS OF ARCHAEAN GRANITE-GREENSTONE TERRANES AS EXEMPLIFIED BY THE BARBERTON MOUNTAIN LAND, SOUTHERN AFRICA

ABSTRACT

Archaean granite-greenstone terranes are characterized by dominantly gravity-induced deformational styles that accompanied the emplacement of granitic magmas and diapiric plutons. The distinctive pattern of relationships between greenstone belts and their surrounding granitic terrane (the "granite-greenstone pattern" of Macgregor, 1951 and Anhaeusser *et al.*, 1969) can be demonstrated over a wide range of scales. These and other structures typical of the kind commonly encountered within deformed Archaean greenstone belts and in their enveloping granitic terranes are illustrated in this contribution by means of schematic diagrams and photographic sets depicting examples derived mainly from the Barberton Mountain Land in southern Africa.

oOo

STRUCTURAL ELEMENTS OF ARCHAEAN GRANITE-GREENSTONE TERRANES AS EXEMPLIFIED BY THE BARBERTON MOUNTAIN LAND, SOUTHERN AFRICA

CONTENTS

oOo

Published by the Economic Geology Research Unit
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg 2001

ISBN 0 85494 791 4

STRUCTURAL ELEMENTS OF ARCHAEAN GRANITE-GREENSTONE TERRANES AS EXEMPLIFIED BY THE BARBERTON MOUNTAIN LAND, SOUTHERN AFRICA

I. INTRODUCTION

Detailed structural investigations in Archaean granite-greenstone terranes have revealed histories of repeated deformation. While there is still much debate as to the fundamental mechanisms responsible for the tectonic evolution of Archaean environments, there is some consensus that tectonic processes have themselves evolved progressively throughout geologic time. Whereas plate-tectonic models provide viable mechanisms for Phanerozoic orogeny and crustal evolution it has not been demonstrated satisfactorily that these processes, unless in modified form, were responsible for tectonic and crust-forming events in the Archaean and Proterozoic.

Archaean structural styles, while locally comparable to deformed sequences in other geotectonic environments, require examination on a variety of scales before a full appreciation of their diversity and distinctive characteristics can be adequately demonstrated. In this contribution the pricipal tectonic elements of Archaean granite-greenstone terranes are illustrated using examples mainly from southern Africa. Specific emphasis is given to structural features encountered in the 3,5 - 3,0 Ga Barberton Mountain Land located on the Kaapvaal Craton in the Eastern Transvaal and Swaziland (Anhaeusser *et al.*, 1983). In this region granite emplacement (both in the form of magmatic intrusive bodies and as subsolidus diapiric plutons) has been responsible for the development of distinctive superimposed structures and textures in an environment that may also have been influenced by an earlier, little understood, deformation episode.

II. THE ARCHAEAN GRANITE-GREENSTONE PATTERN

Most maps depicting greenstone belts within ancient cratons reveal a distinctive pattern of relationships between the belts themselves and their surrounding granitic terrane. This typical "granite-greenstone pattern" (Anhaeusser *et al.*, 1969; Anhaeusser, 1975) is exemplified by Macgregor's (1951) "gregarious batholith" map of the Rhodesian Craton (Fig. 1a) as well as the arcuate form displayed by the greenstone belts in the Salisbury (now Harare) and Belingwe regions of Zimbabwe and in the East Pilbara district of Western Australia (Fig. 1 b-d). The distinctive patterns are largely the response to gravitational adjustments that involved the downsagging of volcano-sedimentary greenstone sequences and the concomitant upwelling of granitic magmas, solid-state diapiric plutons or isostatically unstable, complex migmatite-gneiss terranes. In some granite-greenstone environments, evidence exists for an ensialic basement to the supracrustal sequences while in others, such as in the Barberton region, an initial ensimatic domain is indicated. In the latter environment the tectonic history is envisaged as having developed in a number of stages. An early stage involved large-scale gravitational instability of ensimatic lithosphere and initiated slumping of the developing volcanic pile (Fig. 2a). This may, however, have been preceded by earlier deformation of the volcano-sedimentary sequences

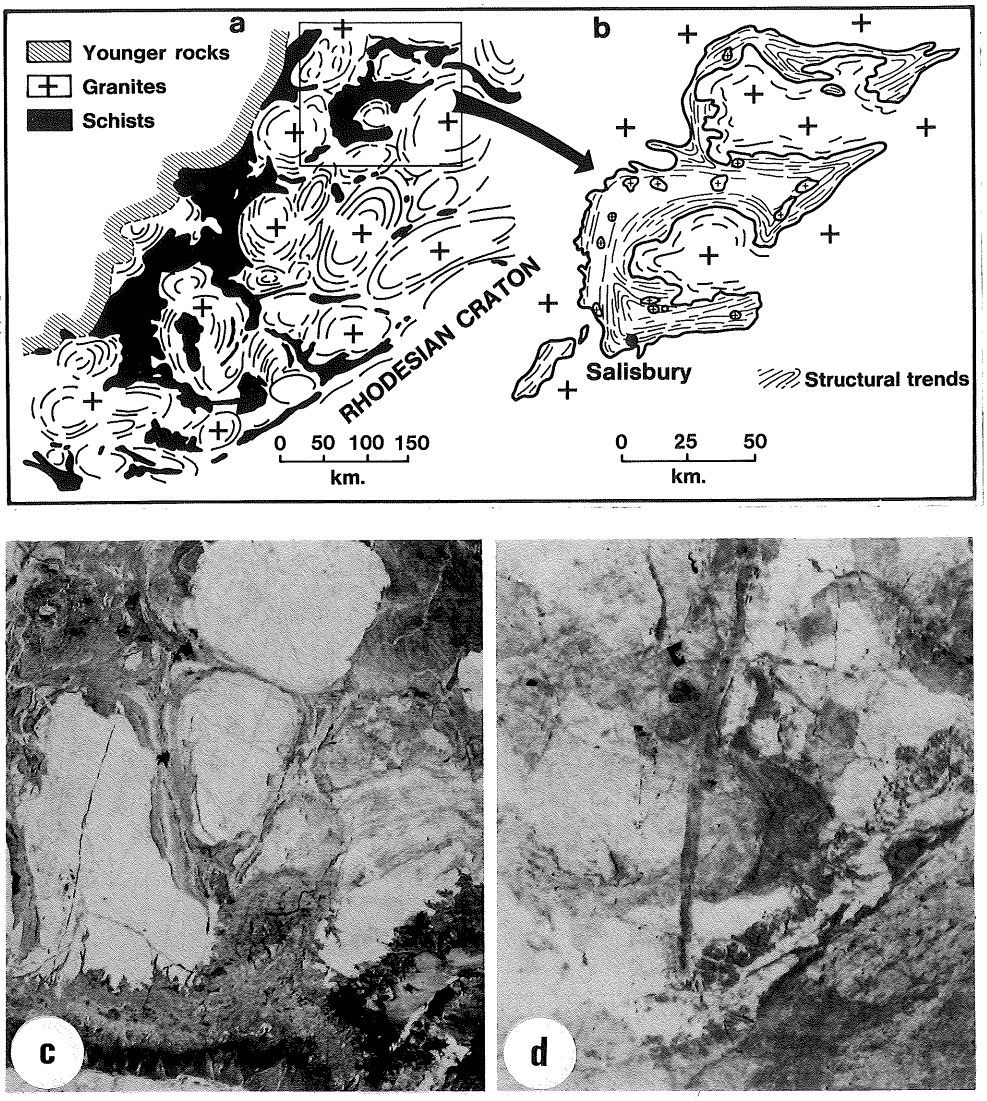


Figure 1 : *Archaean structural style typified by (a) the "gregarious batholith" map of the Rhodesian Craton (after Macgregor, 1951); (b) the arcuate "granite-greenstone pattern" resulting from granite diapirism in the Salisbury-Mt. Darwin greenstone belt, Zimbabwe; (c) ERTS image No. 1148-01281, December, 1972 showing the granite-greenstone geotectonic pattern illustrated by the East Pilbara region of Western Australia, and (d) ERTS image No. 1049-07290, September, 1972 covering part of the southern portion of Zimbabwe, showing the contrasting tectonic styles illustrated by the granite-greenstone terrane of the Rhodesian Craton and the north marginal zone of the Limpopo Mobile Belt. The Great Dyke is also clearly visible. (a) and (b) after Anhaeusser, 1975, with permission from Annual Review of Earth and Planetary Sciences, 3, 40. Copyright 1975 by Annual Reviews Inc., (c) and (d) after Viljoen et al., 1975).*

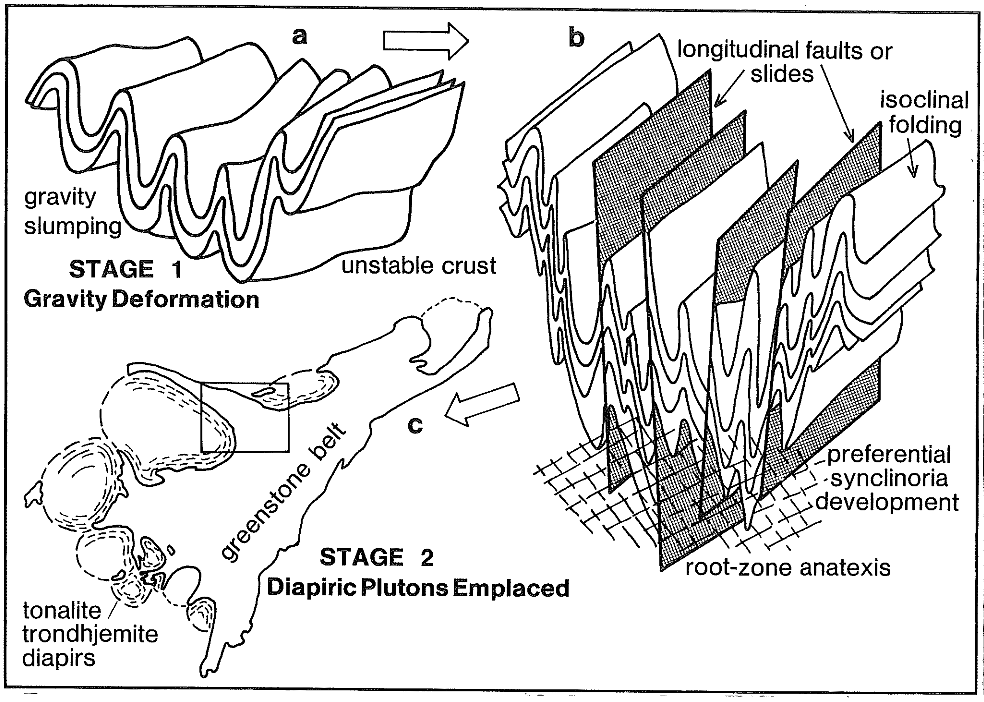
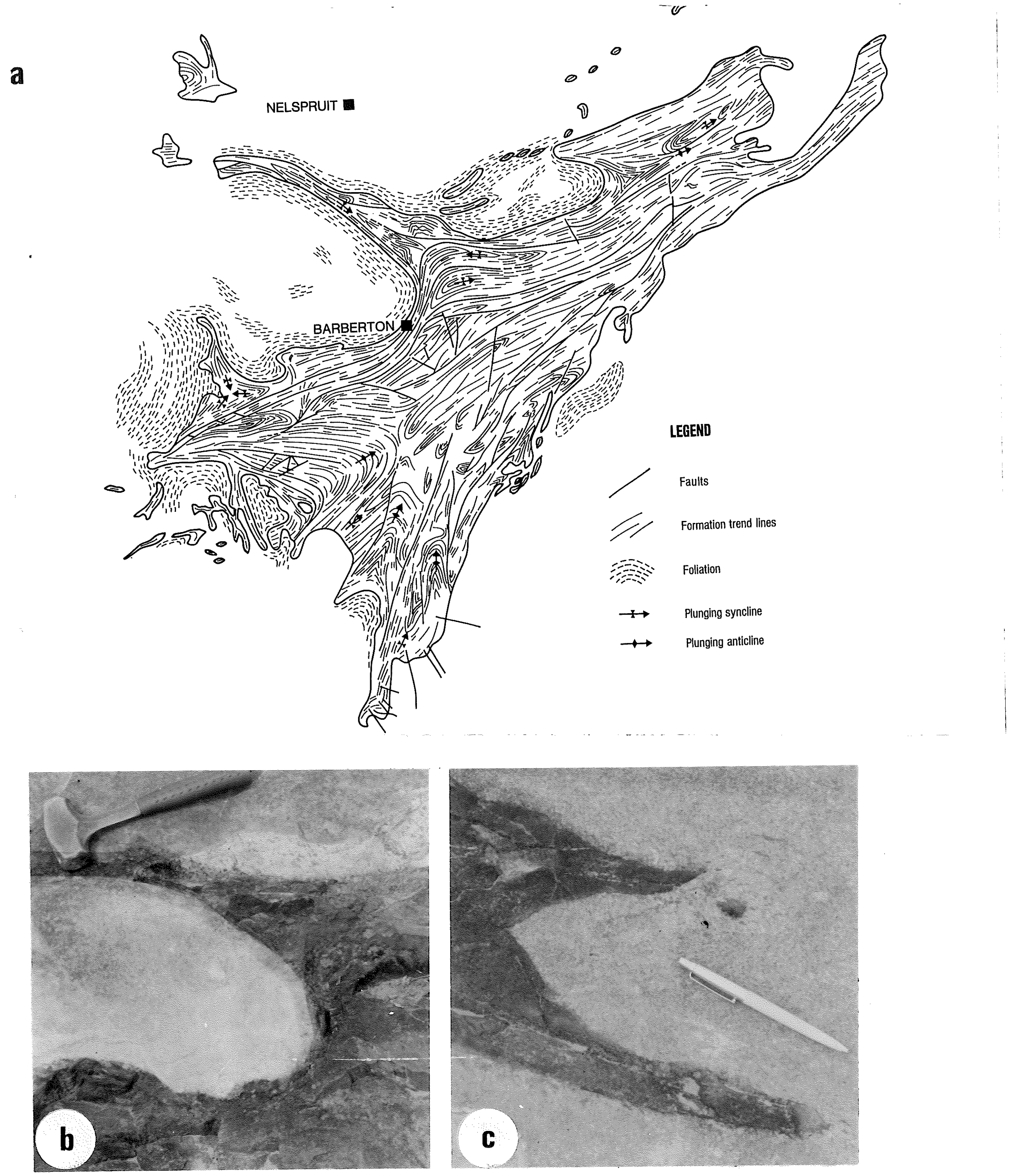


Figure 2 : *Diagrams illustrating schematically the episodic stages of deformation responsible for the tectonic evolution of Archaean greenstone belts. The deformation, which is believed to be largely gravity induced, involves progressive flexuring and slumping and is accompanied by later granite diapirism. The diapiric plutons are, in turn, responsible for the development of most of the structures encountered in greenstone belts — see Figs. 3 and 4 for details (after Anhaeusser, 1975, with permission from Annual Review of Earth and Planetary Sciences, 3, 42. Copyright 1975 by Annual Reviews Inc.)*

(possibly involving horizontal shortening and thrusting), but this remains speculative at this stage. As the gravity induced deformation proceeded (Anhaeusser, 1975; Ehlers, 1978) the infolded sequences were isoclinally folded and steeply inclined longitudinal faults or slides were generated in preferentially developing synclinoria (Fig. 2b). Progressive greenstone deformation followed as a consequence of the upward intrusion of granitic bodies (Fig. 2c), many of which were emplaced as granite diapirs. These diapiric tonalite/trondhjemite plutons are envisaged as having formed from coalescing partial melts derived from high magnesian komatiitic basalts. Some of these bodies were intruded magmatically while still others consolidated to form subsolidus diapirs that were emplaced as a consequence of density inversion. The diapirism produced structures that were superimposed onto successions that may already have possessed a complex structural pre-history.

Figure 3a illustrates the typical development of early isoclinal folding and faulting and its expression regionally in the Barberton greenstone belt. Anticlines, thrusts and nappe-like folds are less common structures in greenstone sequences but have been reported from the Selukwe and Gwanda areas in Zimbabwe (Stowe, 1974; Wright, 1975; Coward *et al.*, 1976), the Tati and Matsitama areas of Botswana (Mason, 1973; Coomer *et al.*, 1977), and in the Barberton belt (Anhaeusser *et al.*, 1968; De Wit, 1982; De Wit *et al.*, 1983).



<u>Figure 3</u> : *Large- and small-scale structural features associated with the Barberton greenstone belt in southern Africa. The greenstone successions underwent early-stage regional deformation involving isoclinal folding and the development of major tectonic slides and high-angle thrust faults (a) which were responsible for segmenting the belt into preferentially developed synclinoria (modified after Anhaeusser et al., 1968). Granite diapirism caused localized deformation and the superimposition of structures onto the early regional tectonic fabric. Diapirism in granite-greenstone terranes can occur at scales ranging from batholithic dimensions (see Fig. 1) down to small pluton sizes. Small-scale structures associated with amphibolite xenoliths in the trondhjemitic gneisses south of the Barberton greenstone belt (b and c) illustrate a high degree of correspondence with features recorded in and adjacent to the larger greenstone parent (a).*

On a vastly differing scale, but almost identical to their larger counterparts down to the finest detail, are structures featured in xenoliths found in the granites enveloping the greenstone belts. Comparison of Figs. 3b and 3c with the Barberton structural map (Fig. 3a) shows remarkable correspondence suggesting that structures developed in the Archaean, involving granite emplacement, are not scale dependant. The processes whereby structures of the type shown in Fig. 3 formed may, however, differ. The larger structures (seen in Figs. 1 and 3a) are envisaged as having formed mainly by subsolidus diapirism on a variety of scales where density contrasts and gravitational forces were considerable. The smaller structures (seen in Fig. 3b and 3c) can not be directly related to gravity deformation for, on the scale of a few metres, the density contrast is negligible. There is also no apparent evidence to suggest that these structures formed by a series of compressive strains resulting in what might be construed as dome and basin interference folding. Instead, they are the direct result of magmatic intrusion.

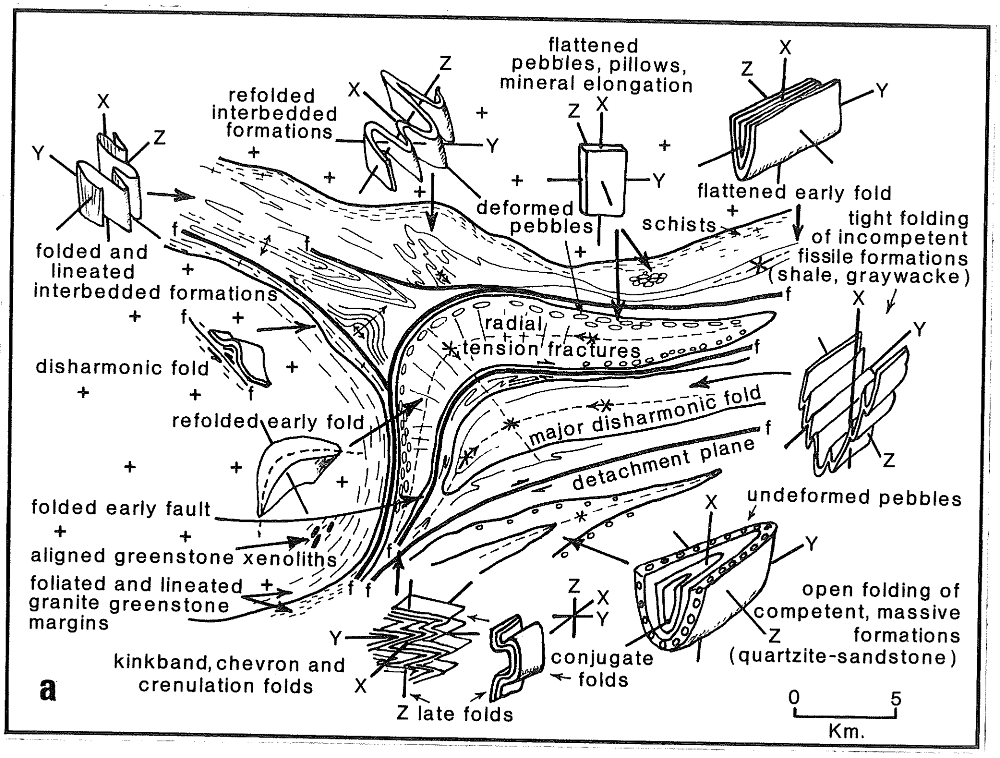
III. STRUCTURES PRODUCED BY GRANITE DIAPIRISM

Although cross buckling and other types of cross folding can produce domical structures (Fyson, 1978; Schwerdtner *et al.*, 1978; Platt, 1980) most conformable Archaean structures are considered to result from diapirs formed as a result of the buoyant rise of low-density material into a high-density ductile overburden (Sorgenfrei, 1971; Clifford, 1972; Ramberg, 1973, 1981; Anhaeusser, 1975; Stephansson, 1975, 1977; Drury, 1977; Fyson *et al.*, 1978; Schwerdtner *et al.*, 1979; Davidson, 1980; Borradaile, 1982).

Structures typically resulting from granite diapirism are portrayed in Fig. 4a which schematically illustrates part of the Barberton greenstone belt. Aerial photographic views of the Eureka and Ulundi synclines (two major refolded folds, Fig. 4b), and the Handsup-Mundt's Concession folds (the first a major disharmonic fold and the second a major anticlinal structure, Fig. 4c) demonstrate the complex and varied nature of the deformation styles that may be encountered in juxtaposed sequences of differing compositions and ductility contrasts.

Greenstone successions are characterized by diverse lithologies ranging from mafic and ultramafic plutonic and extrusive sequences to assemblages consisting of mafic-to-felsic volcanic, plutonic and pyroclastic rocks and a wide range of metamorphosed pelitic, psammitic and chemical sediments. Numerous components within the volcano-sedimentary successions can be employed as strain indicators in the deformed greenstone sequences. Examples of some relatively undeformed features such as spherules (or ocelli), conglomerates and pillow lavas are shown in Fig. 5 and compared with strained equivalents from areas of the greenstone belt influenced by granite diapirism (see Fig. 4a). Deformed spherules, oolites and polymictic conglomerate pebbles as well as folds have been used to calculate the total finite strains experienced by the rocks at different localities (Ramsay, 1963; Anhaeusser, 1969a, b; Gay, 1969).

A further manifestation of the tectonic complexity of the region shown in Fig. 4a can be demonstrated in the refolded volcano-sedimentary successions located in the vicinity of the New Consort Gold Mine north-west of the Eureka syncline. Superimposed deformation has resulted in an intricate pattern of folding and refolding of the mineralized siliceous chert unit in the mine area (Fig. 6a). Examples of some of the folds encountered in the area are illustrated in Figs. 6b-d.



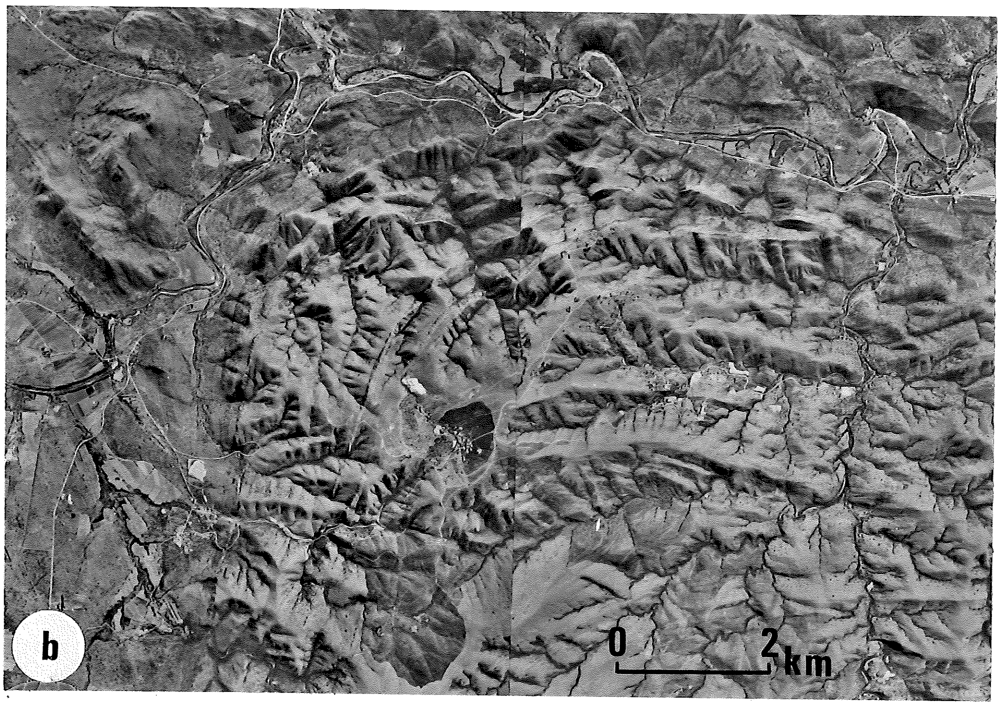


Figure 4 : *See explanation to Fig. 4a - c on next page*

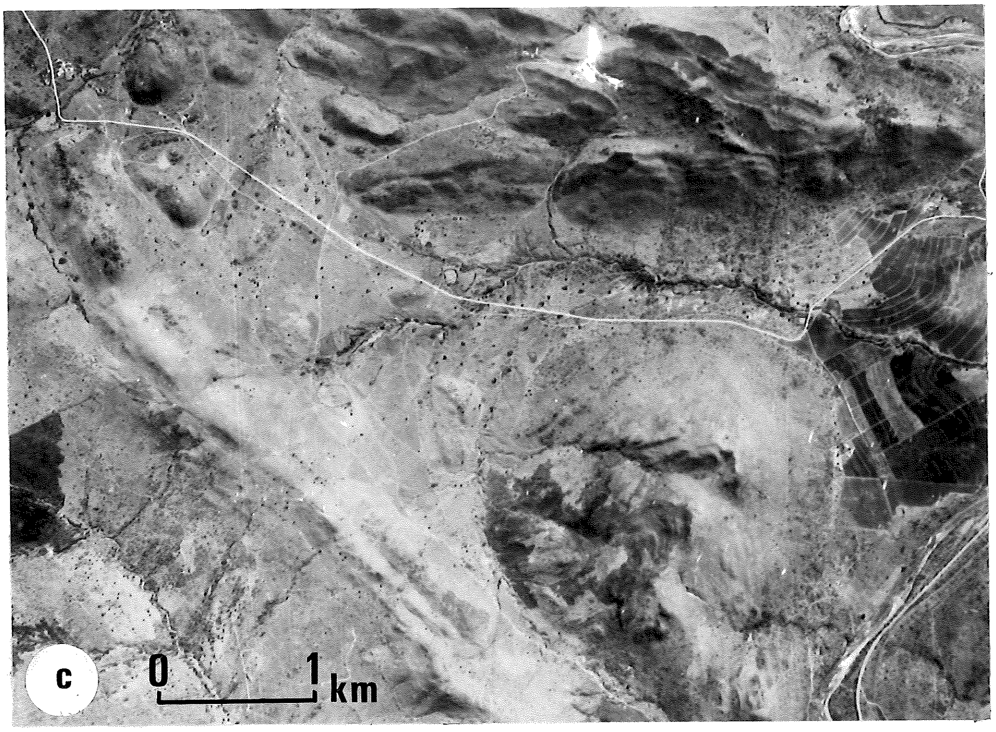


Figure 4 : *Schematic diagram (a) illustrating the main tectonic elements and strain indicators in an Archaean greenstone belt deformed by the emplacement of diapiric granite plutons. Region depicted is outlined in Fig. 2c and forms part of the Barberton greenstone belt in southern Africa (after Anhaeusser, 1975, with permission from Annual Review of Earth and Planetary Sciences, 3, 43. Copyright 1975 by Annual Reviews Inc.). The large refolded synclinoria, shown in the schematic diagram, are depicted in the aerial photographic view of the Eureka and Ulundi synclines. In Fig. 4a X, Y and Z represent the axes of maximum, intermediate and minimum elongation, respectively. (b) The folding and faulting in the area has provided a favourable structural environment for the development of epigenetic gold-quartz vein deposits. North-west of the arcuate structures, composed of refolded argillaceous and arenaceous sediments of the Fig Tree and Moodies groups, are folded layered mafic and ultramafic assemblages associated with the Onverwacht Group. The aerial photographic view (c) shows the Handsup disharmonic fold (lower-right) produced by left-lateral detachment along the north-west-striking Albion fault (Anhaeusser, 1972 — see also schematic diagram (a)). The Mundt's Concession anticline (layered ultramafic complex, upper half of photograph) and the Handsup disharmonic fold are part of the same succession but are separated by zones of shearing. Chrysotile asbestos, a stress-produced fibre, has been mined from the dunites in the core of Mundt's Concession fold.*

Granite diapirism causes layer-parallel extension and flattening of the successions into which the body is emplaced. This attenuation is manifest in the development of schists and phyllites in the volcanic and sedimentary successions adjacent to the deforming granitic bodies. It also leads to the development of a wide variety of folds, some examples of which are illustrated in Fig. 7. The nature and style of the folds depends on the ductility contrasts

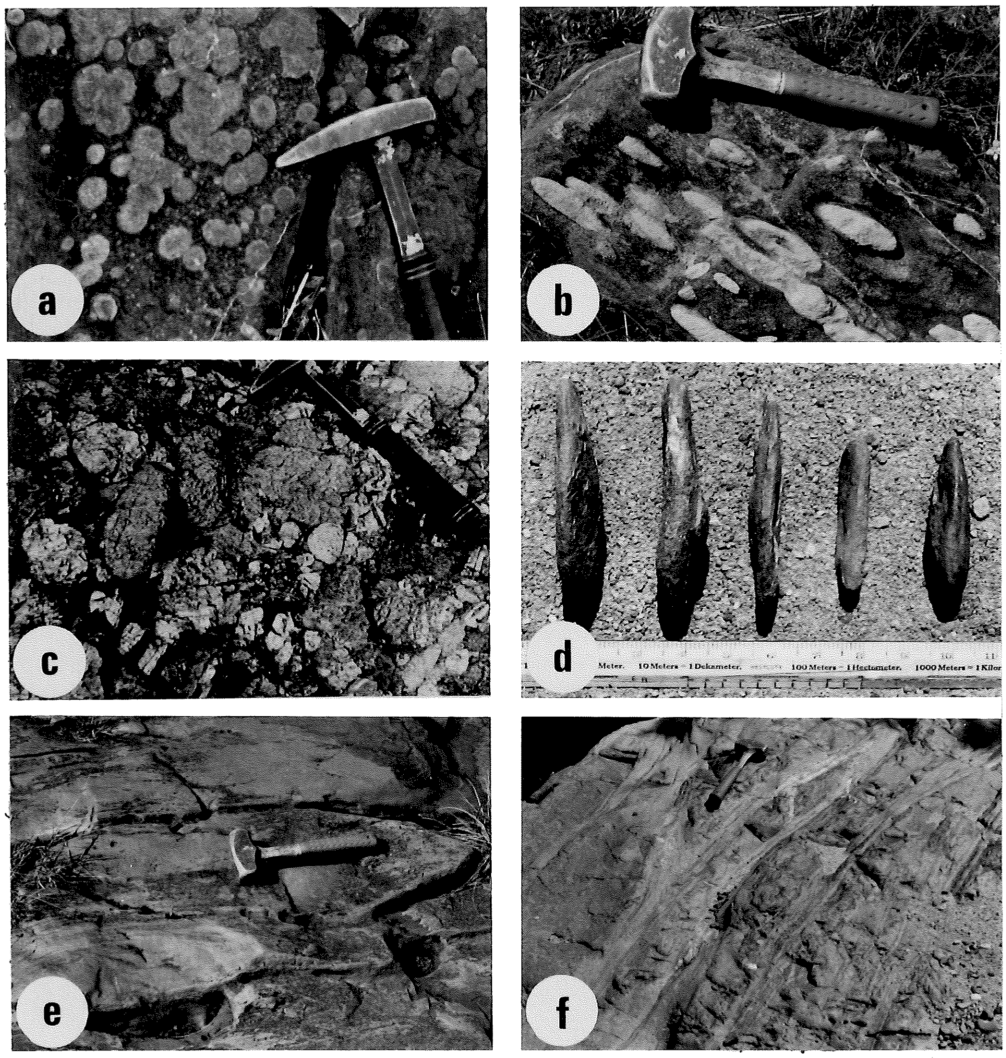


Figure 5 : *Comparison of some relatively undeformed versus deformed strain indicators found in Archaean volcano-sedimentary successions. (a) Spherical orbicular structures (ocelli) developed in unstrained basaltic komatiites (Anhaeusser, 1972). (b) Flattened ocelli in hornblende amphibolites (metabasaltic komatiites) from the contact aureole of the Nelshoogte diapiric gneiss pluton (Fig. 8). (c) Relatively undeformed pebbles in Moodies conglomerates on the southern limb of the Eureka syncline (Fig. 4b) 5 km from the contact zone of the Stentor diapiric gneiss pluton (Anhaeusser, 1976; Anhaeusser et al., 1983). (d) Flattened chert pebbles from the Moodies conglomerates on the north limb of the Eureka syncline 1,8 km from the Stentor diapiric gneiss pluton. Calculations of the total finite strain of the conglomerate pebbles in the Eureka syncline yielded pebble extension values of 19 per cent (south limb pebbles, Fig. 5c) and 49 per cent (north limb pebbles, Fig. 5d) (Anhaeusser, 1976). (e) Elongated, bulbous, load-flattened pillow basalts and (f) YZ plane of pillows flattened by diapir-induced stress. Maximum extension (X) occurs at right angles to the plane of the exposed surface.*

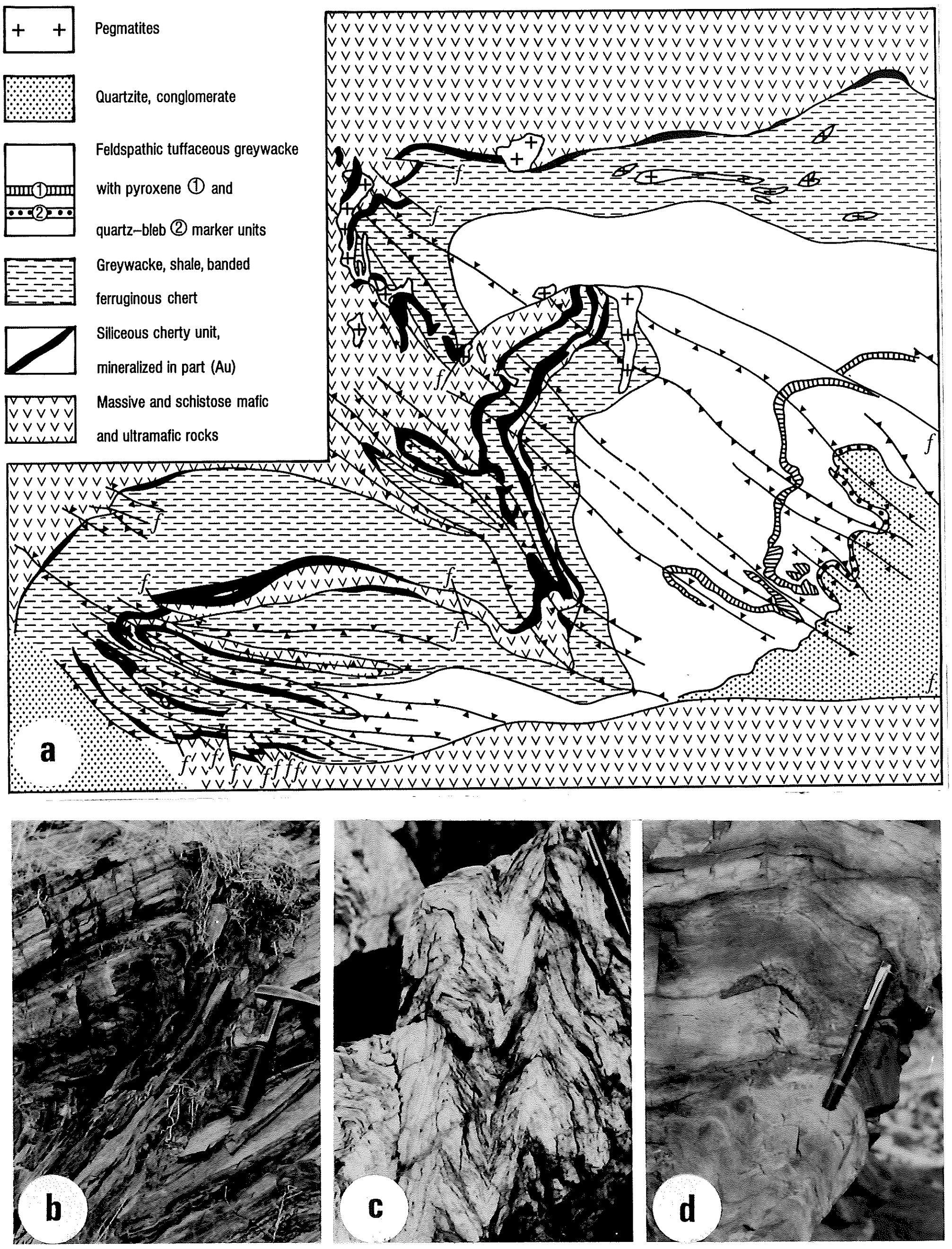


Figure 6 : *Complex superimposed folding in the vicinity of the New Consort Gold Mine north-west of the Eureka syncline in the Barberton greenstone belt (see also Fig. 4). Early NE-SW-trending folds have duplicated the siliceous mineralized cherty unit which, in turn, has been refolded about NW-SE fold axes (modified after Viljoen, 1963 and Anhaeusser, 1972). (b) Tightly folded Fig Tree shales and greywackes in the New Consort Mine area. A minor thrust fault separates the anticline seen on the left from a second anticline to the right of the geological hammer. (c) Chevron (accordion) folds superimposed on a previously deformed quartz-sericite schist unit interlayered with mafic and ultramafic schists in the southern portion of the geological map. (d) Flattened carbonaceous chert pebble in Fig Tree greywackes folded by the later refolding event in the New Consort Mine area (b, c and d after Anhaeusser, 1972).*

Figure 7 : *Examples of fold and related structures developed in Archaean granite-greenstone terranes. (a) Folded and boudinaged granitic dykes intruded into metabasalts along the tectonized northern contact of the Barberton greenstone belt (after Anhaeusser, 1966). (b) Ptygmatically folded anatectic vein in an amphibolite xenolith intruded by trondhjemite gneisses. The cusp-like structures, developed in the Theeboom river exposure south of the Barberton greenstone belt (Robb, 1982), are characteristic of the form assumed by a strongly compressed contact separating material of different viscosities. The amphibolite has the lower viscosity. (c) Isoclinally folded banded iron-formation of the Fig Tree Group in the Barberton greenstone belt. The folded white layers consists of chert and the darker bands comprise silicified shales. Ductility contrasts are responsible for folding of the chert layers and boudinaging of the shale layers. Tension cracks filled with vein quartz are developed perpendicular to the extension direction which is parallel to the fold axial trace. (d) Early-formed isoclinal folds in banded iron-formations in the Lily Gold Mine, Barberton area. Differential shortening caused variations in the fold plunges. Measurements carried out on the folds, which are close to the northern contact of the Barberton greenstone belt, suggest they have undergone approximately 63 per cent combined buckling and pure shear deformation (Anhaeusser, 1969a). (e) Vertical exposure of late-phase chevron folds with sub-horizontal fold axes developed in feldspathic quartzites of the Moodies Group in the Eureka syncline (Anhaeusser, 1976). (f) Conjugate fold in thin-bedded shales and subgreywackes of the Moodies Group. The conjugate folds occur together with minor subhorizontal crenulation folds (right of hammer) and both developed under the influence of a late stage (σ_1 vertical) stress field (Anhaeusser, 1976). (g) Oblique slaty cleavage in vertically dipping Fig Tree shales and greywackes of the Eureka syncline at the Clutha Mine, north of Barberton. Application of the cleavage-bedding rule (Leith, 1923; Wilson, 1961) would suggest that the base of the succession lay to the south (left in photograph) and that the rocks "young" towards the north. However, it has been proved, by graded-bedding in the greywackes, that the beds "young" towards the south and there is, furthermore, no doubt whatever of the true synclinal nature of the Eureka fold. The correct interpretation, and verified by Ramsay (1963) on both a small and a large scale, indicates that the cleavage is superimposed on pre-existing folds. (h) Dome-like structure in Moodies sub-greywackes. Dome and basin structures of this type are produced by the superimposition of two generations of folding. Intersecting anticlines produce domical structures whereas intersecting synclines form basin structures (Ramsay, 1962; Anhaeusser, 1976).*

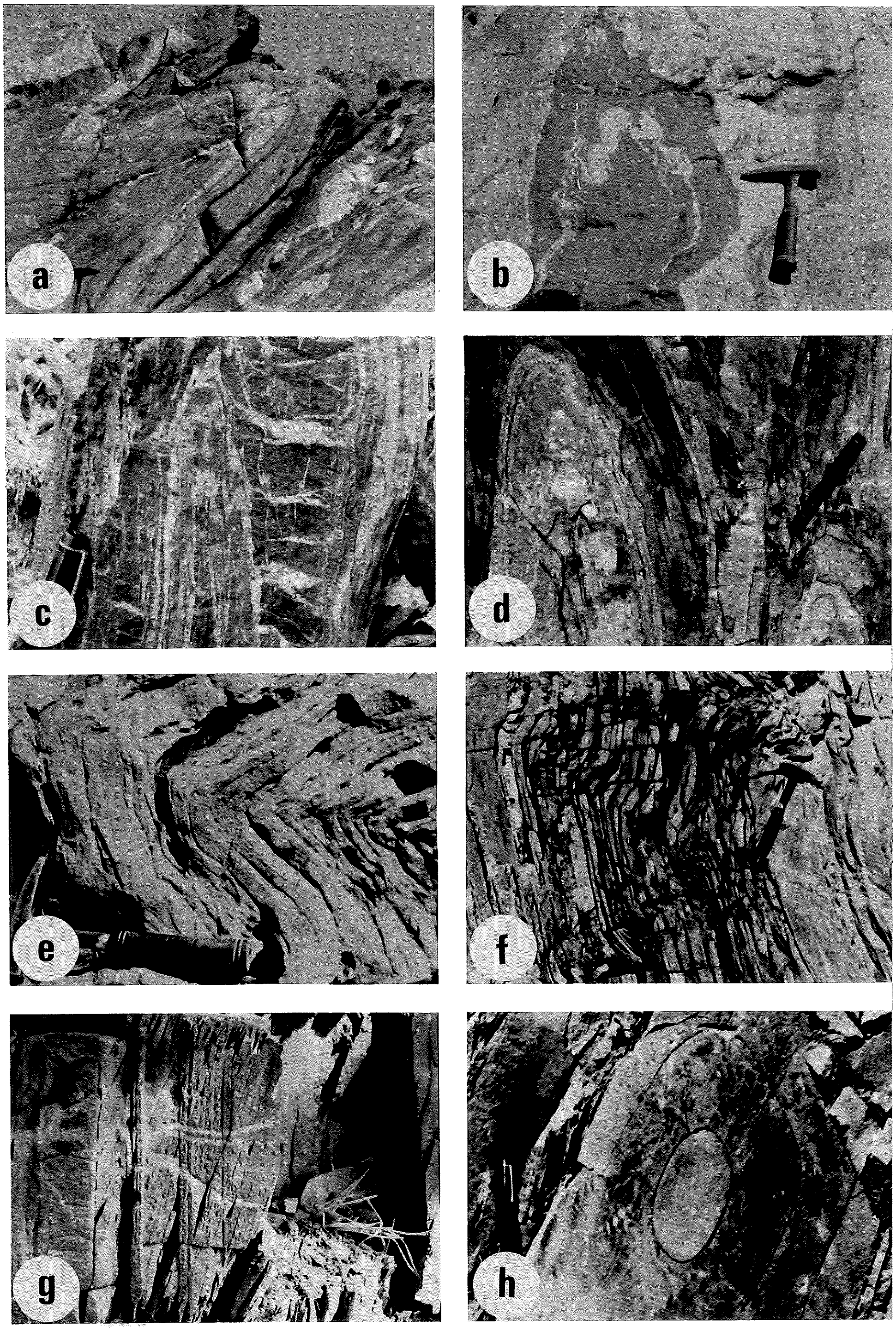


Figure 7 : *See explanation to Fig. 7 on facing page*

of the deformed successions, the degree of shortening, and the attitude of the folded layers relative to the principal compressive stress. Fold attitudes, and their axial plane orientations, can be of assistance in determining principal stress directions (Ramsay, 1963; Anhaeusser, 1976). Slaty cleavage (Fig. 7g) is common in deformed sedimentary sequences in greenstone belts and is usually developed parallel to the median plane of flattening. In some cases cleavage may be used to determine "younging" directions and can be employed to test for the overturning of strata in folded sequences.

The granitic bodies intruded into Archaean greenstone sequences may be emplaced as magmatic, semi-consolidated plutons or as solid diapirs. In the magmatic state xenoliths may be prized off the parent greenstone belt and transgressive contact relationships can be encountered (Fig. 8).

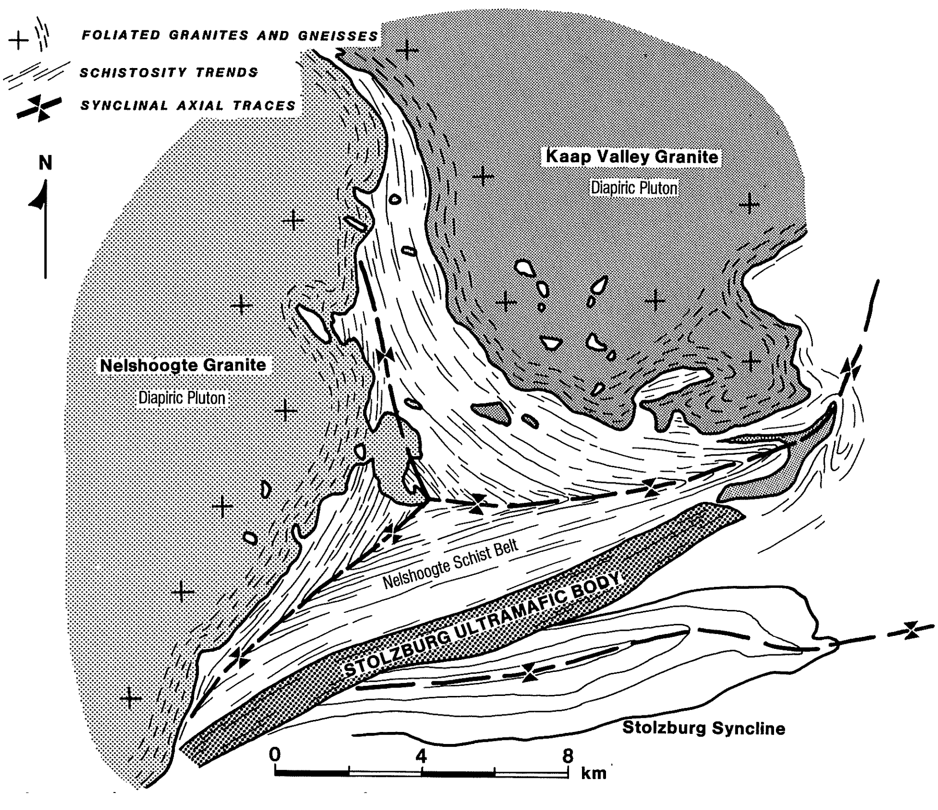


Figure 8 : *Simplified map of the Nelshoogte schist belt in the western sector of the Barberton greenstone belt (see Fig. 3a). The diapiric emplacement of "close packed" tonalite-trondhjemite gneiss plutons and the buttressing effect of the adjacent greenstone sequence in the south-east is responsible for the triangular symmetry of the greenstone belt and for the synformal fold axes that plunge towards the core of the infolded sequences. The invading plutons evolved from early magmatic bodies, responsible for rafting off greenstone fragments to form xenoliths and creating agmatitic contact zones, to solid diapiric gneiss bodies with strongly developed foliations and vertical lineations. The later solid-state diapirism was largely responsible for the structural complexity encountered in the adjacent schist belts as well as for the development of highly tectonized migmatitic granite-greenstone contact zones.*

Two or more plutons emplaced into the volcanic sequences are commonly accompanied by subsidence of the denser overburden into tight triangular synclines (Gorman *et al.*, 1978), the respective fold axes plunging towards the cores of the "sinks" between the "close-packed" plutons.

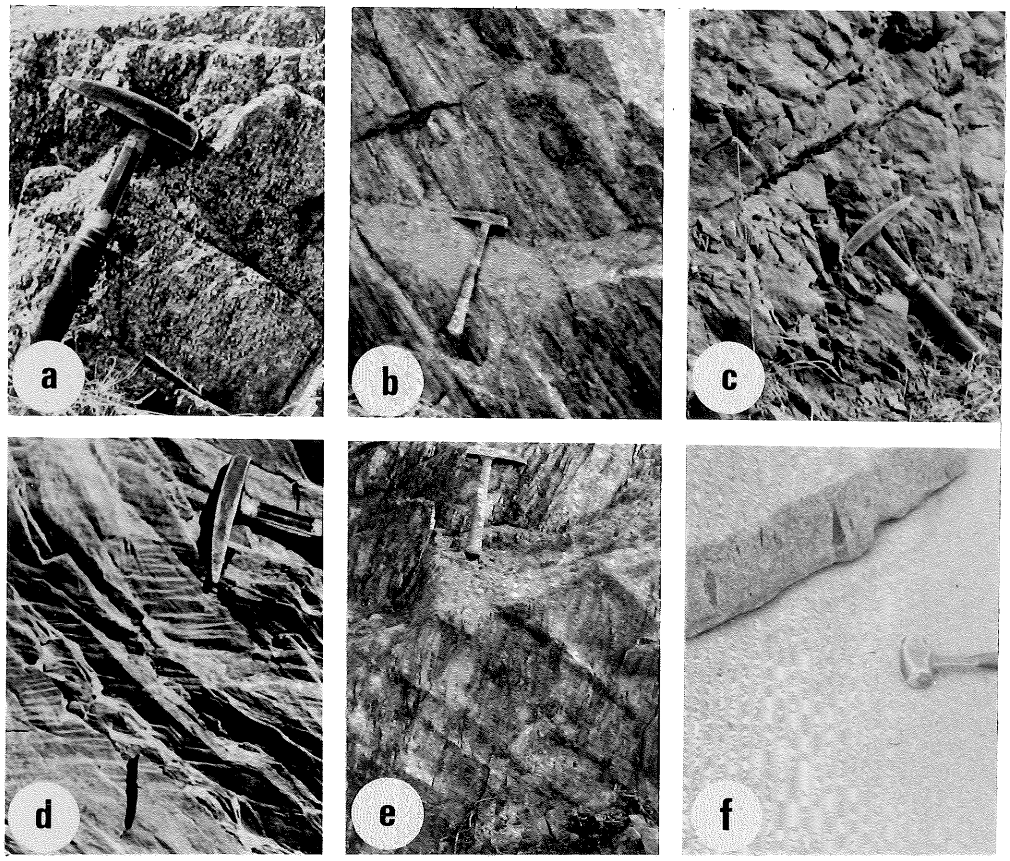


Figure 9 : Linear structural features characteristically encountered in granite-greenstone terranes and related principally to diapiric granite emplacement. (a) Foliated Kaap Valley tonalite gneiss north of Barberton showing a subvertical mineral lineation (parallel to hammer handle) produced by the alignment of biotite and hornblende. (b) Steeply plunging mineral lineation in Onverwacht Group actinolite schists close to the lineated tonalite gneisses seen in Fig. 9a. (c) Shape fabric defined by flattened pebbles of Moodies Group basal conglomerates on the northern limb of the Eureka syncline, Barberton greenstone belt. The deformed pebbles exhibit a uniform plunge of pebble long axes parallel to the pick handle. (d) Crenulation folds (kink-band folds) with horizontal fold axes and axial planes in finely laminated brittle shales and subgreywackes of the Moodies Group. These minor folds are associated with conjugate folds (Fig. 7f) in the Eureka syncline along the Havelock Road. The attitude of the folds suggests they were developed in a vertical stress field σ_1 vertical) (Fig. 9a-d after Anhaeusser, 1976). (e) Onverwacht Group talc-chlorite schists displaying superimposed lineations. The first-formed mineral lineations are sub-vertically orientated parallel to the hammer handle. The later cross-cutting crenulation lineation formed in response to a different stress field. (f) Mafic schlieren in foliated trondhjemitic gneisses (foliation parallel to hammer handle) south of the Barberton greenstone belt. The schlieren are preferentially elongated parallel to a vertical lineation developed in the gneisses.

The rising plutons metamorphosed the greenstones (generally to greenschist or amphibolite grade); foliations, gneissosity and lineations developed in the marginal zones of both the greenstones and the tonalitic or trondhjemitic bodies (Anhaeusser *et al.*, 1969; Anhaeusser, 1975). Some of the distinctive linear structures believed to be related to granite diapirism are shown in Fig. 9.

The magmatic stage of granitic intrusion was sometimes accompanied by the explosive fragmentation of the supracrustal sequences to form agmatites. The progressive solidification and subsequent diapiric uprise of the pluton can be responsible for the deformation of migmatites and the development banded gneisses at some granite-greenstone contacts. Figure 10 shows schematically the nature of the changes that may convert agmatitic zones into banded gneisses following intense flattening and stretching of initially angular, disorientated blocks.

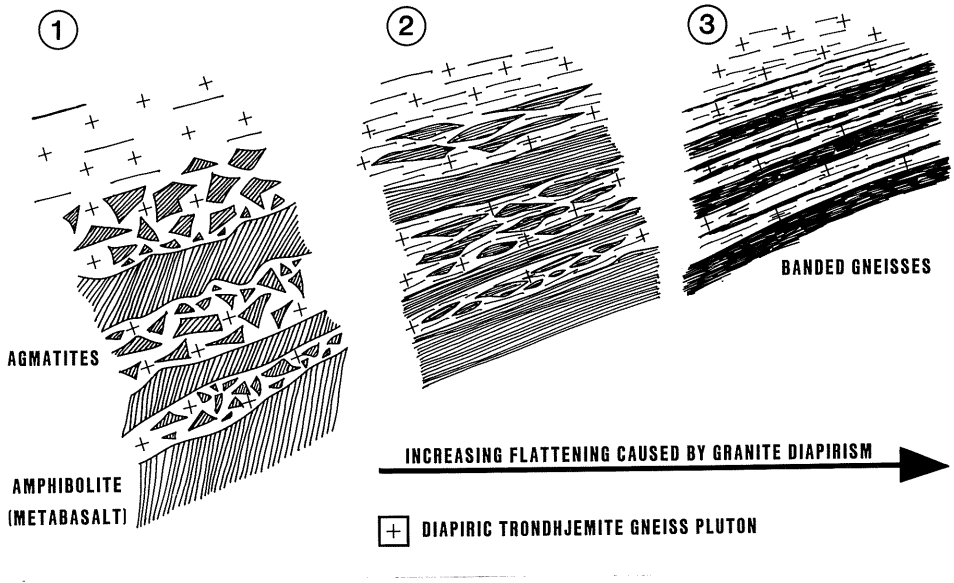
Another contact relationship involves the *lit-par-lit* injection of granitic phases into early-formed foliation planes of deformed greenstone successions. This intrusive style is illustrated in Fig. 11 and can occur at a variety of scales (Anhaeusser and Robb, 1980). If diapiric movement takes place later, flattening may result in the formation of boudin structures like those shown schematically and in the photographs (Fig. 11 b,d). Maximum shortening of the formations occurs normal to the contact zone.

It should be emphasized that it is not easy to differentiate between banded gneisses produced by layer-parallel extension of agmatites or *lit-par-lit* injected granitic phases like those shown in Figs. 10 and 11. A wide variety of processes and differing tectonic circumstances may be responsible for the development of banded gneisses. The examples provided are considered to be locally significant in the immediate contact zones of diapiric plutons south of the Barberton greenstone belt. Banded gneisses found in areas remote from granite-greenstone contacts may owe their origin to entirely different regional tectonic influences.

Structures seen in the granitic terranes enveloping Archaean greenstone belts show considerable variation and degress of complexity. A few illustrations, representative of features noted in some of the tectonized granites in the southern part of the Barberton Mountain Land, are shown in Fig. 12, and include deformed megacrysts (the latter could represent either phenocrysts or porphyroblasts depending upon whether they preceded deformation or whether they were formed syntectonically), folded banded gneisses and foliated trondhjemites, folded migmatitic gneisses and ptygmatic structures.

IV. STRUCTURE AND METAMORPHISM OF GREENSTONE BELTS

Low-grade metamorphism (regional greenschist facies) is typical of the major part of most greenstone belts world-wide. Only close to granite contacts does the metamorphic grade generally increase to medium-grade amphibolite-facies conditions. There is also an intimate relationship between metamorphism and deformation, the sequence usually comprising two or more periods of mineral development and deformation, followed by widespread post-tectonic recrystallization and late-stage retrogression in the waning phases of metamorphism (Anhaeusser *et al.*, 1969).



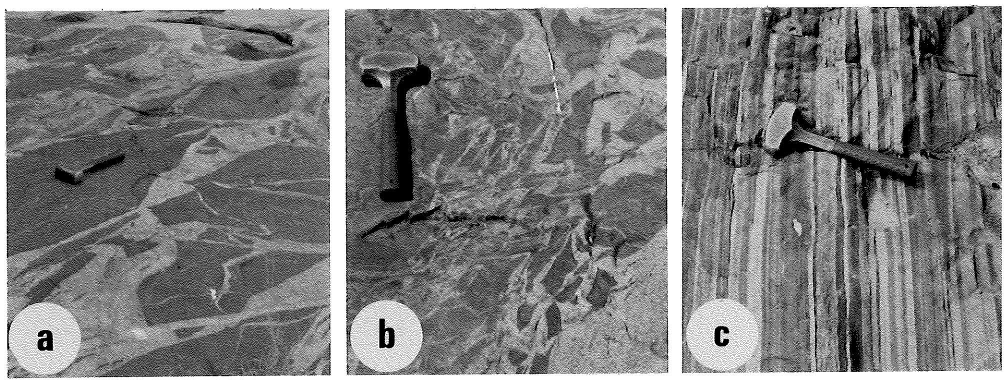
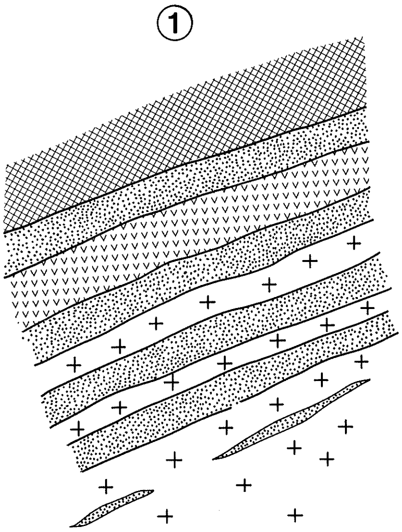
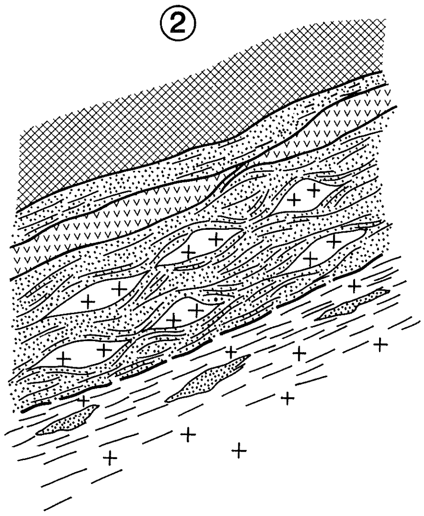


Figure 10 : *Formation of banded gneisses by progressive deformation of agmatites developed during early stages of magmatism and granitic diapirism. The schematic diagram illustrates the changes that occur from zones of low strain (1) in which most fragments of amphibolite are angular and have irregular orientations, to zones of medium strain (2) where the fragments, although still angular, begin to assume an alignment of long axes subparallel to the foliation of the invading trondhjemitic gneisses. Continued diapiric uprise produces zones of very high strain in which the amphibolite blocks are intensely flattened and streaked out into more regularly banded amphibole and quartzo-feldspathic gneisses in a manner similar to that described for the Archaean gneisses of Greenland (Myers, 1978). A series of photographs (a-c) from the granite-greenstone contact areas of the Theespruit and Uitgevonden plutons south of the Barberton greenstone belt illustrate the suggested nature of the changes that may accompany the increasing strain inflicted by the upward movement of rising diapirs under amphibolite facies metamorphic conditions. Field exposure limitations render it impossible to trace continuously the progressive stages of deformation indicated schematically in diagrams 1-3.*

Figure 11 : *Schematic diagrams (1 and 2) illustrating a plan view of the style of deformation that may accompany lit-par-lit intrusion and later tectonism in contact zones of greenstone belts and diapiric gneiss plutons. The example is from the southern contact of the Weergevonden greenstone remnant south of the Barberton greenstone belt (Anhaeusser, 1980). Photographs (a) and (c) show trondhjemitic gneisses intruded into subvertical amphibolite schists in a low strain environment. The lit-par-lit intrusions also occur at scales larger and smaller than illustrated (Anhaeusser and Robb, 1980), the magma being injected from below into schistosity planes in the supracrustal sequences that were developed early in the diapiric evolution. In high strain environments the adjacent greenstone sequences undergo attenuation to produce structures like those shown in Figs. 5-7, while in the contact zones of diapiric plutons, boudinage structures (b and d), migmatites and banded gneisses are commonly formed. Photograph (b) shows boudinaged banded amphibolite gneiss with quartzo-feldspathic stringers and in (d) trondhjemite gneiss boudins (lower left and beneath hammer) occur in banded and foliated felsic schist (altered felsic tuff). Quartz veins and anatectic stringers occur in the schists and fill voids between the boudinaged gneisses (Anhaeusser, 1980). All the photographs are from the area south of the Barberton greenstone belt and described by Anhaeusser and Robb (1980).*



LIT-PAR-LIT INTRUSION OF TRONDHJEMITE INTO SUBVERTICAL GREENSTONE SEQUENCE



BOUDINAGE STRUCTURES RESULTING FROM INCREASED FLATTENING ACCOMPANYING GRANITE DIAPIRISM

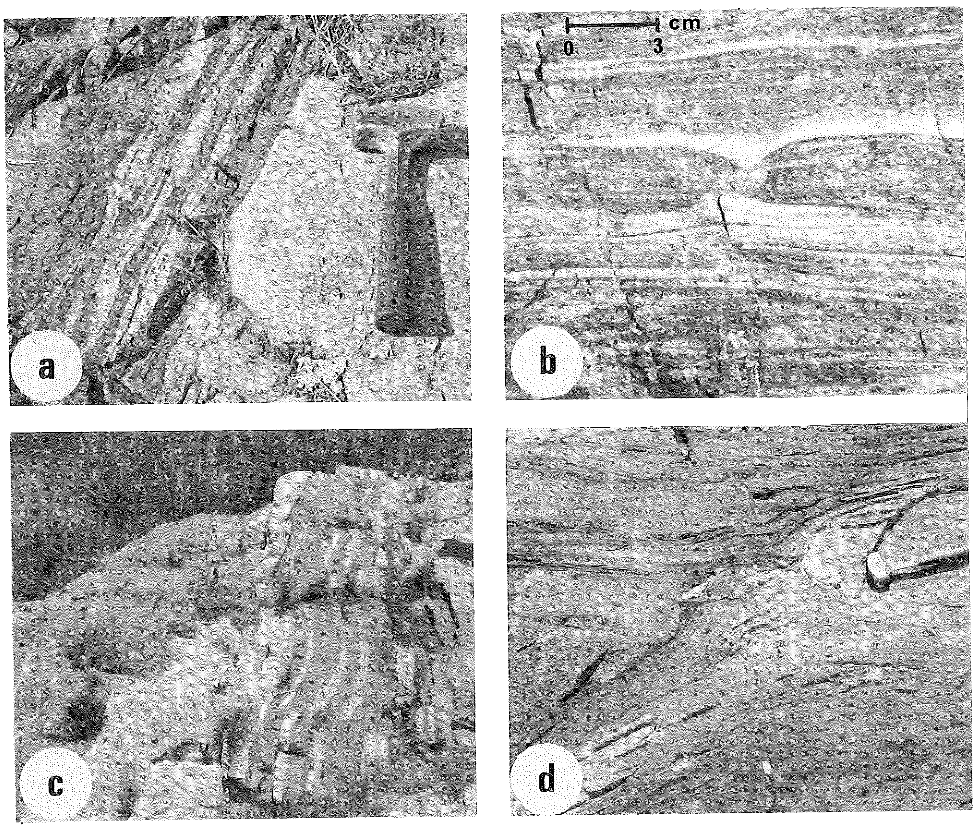


Figure 11 : *See explanation to Fig. 11 on facing page*

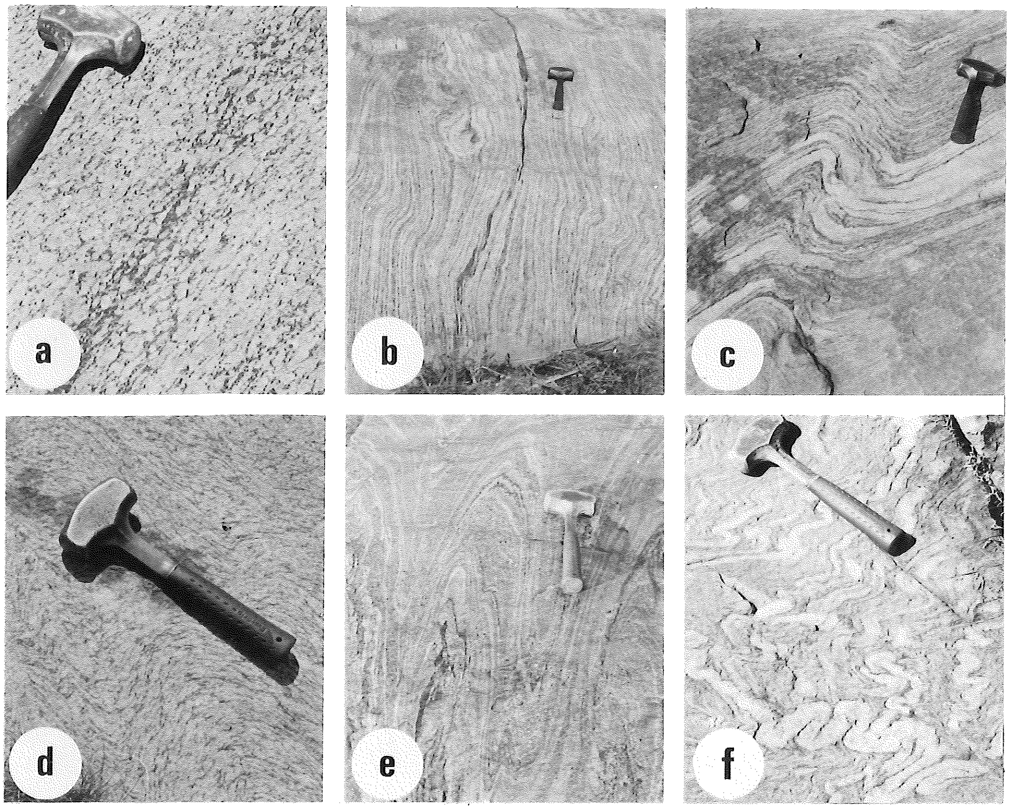


Figure 12 : *Tectonic styles encountered in the Archaean granitic terrane in the vicinity of the Barberton greenstone belt. (a) Preferentially aligned orthoclase and orthoclase microperthite porphyroblasts in deformed syenite. The porphyroblasts occur as prolate ellipsoids recrystallized and deformed with a matrix of microcline, plagioclase, biotite and quartz. (b) Banded and foliated trondhjemitic gneisses (venitic banded gneiss-migmatite) separated into leucosomes and melanosomes (lighter and darker bands, respectively). A mafic dyke (or attenuated greenstone xenolith ?) contributes to the stromatic layering in the high strain environment. (c) Z-shaped fold in banded and foliated trondhjemite gneisses. These and S-shaped folds are encountered on the limbs of larger (even regional) structures and M- or W-shaped folds occupy hinge zones. (d) Strongly foliated and crenulated leuco-biotite trondhjemite gneisses from the crestal zone of a diapiric gneiss pluton partly enveloped by an arcuate greenstone xenolithic remnant in the southern part of the Barberton greenstone belt (Fig. 3a). The crenulated foliation results from a superimposed increment of strain on an early-formed foliated gneiss. (e) Complexly folded migmatites and gneisses typical of the type found flanking greenstone septa wedged between trondhjemitic gneiss plutons in the southern part of the Barberton Mountain Land. (f) Ptygmatic structures ("entrail migmatites") in heterogeneous gneiss-migmatite. The disharmonic, tortuously folded, light-coloured bands represent deformed anatectic veins in the felsic host rock. Photographs a, b and f after Anhaeusser (1980).*

The low-grade metamorphism generally accompanied the early regional deformation in the form of gravity-induced slumping, sliding and, in some cases, thrusting (see Fig. 2b). Depending upon the availability of suitable lithological types involved in deformation, the early tectonic events formed penetrative as well as non-penetrative schistosity defined by micas, chlorites and amphiboles. These, and a few other mineral species, can, for the purposes of this discussion, be regarded as F1 fabrics (Fig. 13). It should be noted, however, that

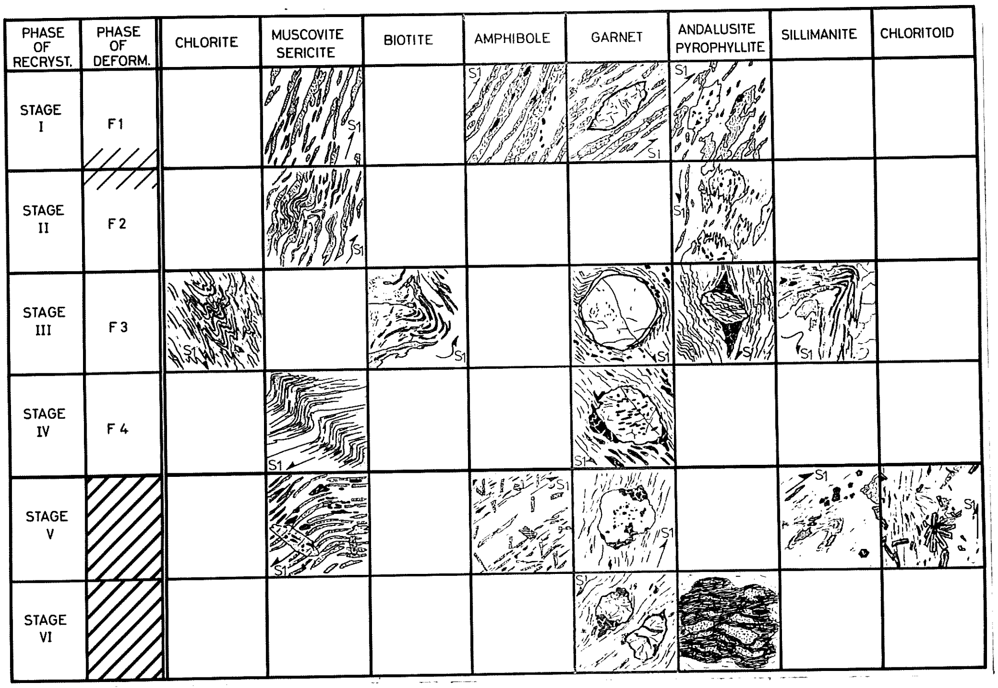


Figure 13 : *Diagram (after Anhaeusser, 1969b) illustrating the structural and mineralogical evolution of metamorphic assemblages in the northern sector of the Barberton greenstone belt (in the vicinity of the New Consort Mine, see Fig. 6a), based on field and microscopic observations. In the Barberton belt deformation phases F1 and F2 may, in part, coincide with the regional tectonic episode involving isoclinal folding (see Fig. 2b). Equally, the diapiric emplacement of tonalite-trondhjemite plutons in the area may be responsible for the strong mineral alignment (schistosity S1). Subsequent superimposed folding (F3 and F4, as determined in the area north of Barberton by Ramsay, 1963 and Anhaeusser, 1969b, 1976) involved progressive stages of diapiric uprise as well as local movements along subvertical fault and shear planes. During deformation stage F3 earlier-formed fabrics were folded and porphyroblasts were rotated. An episode of post-kinematic recrystallization is seen in the form of mineral overgrowths (Stage IV recrystallization phase) and late stage deformation is usually manifest in the form of crenulation or kink-band folding of earlier planar or even crenulated schistosity surfaces. Further rotation of porphyroblasts may have accompanied late stage tectonic activity. A final recrystallization phase (Stage VI) took the form of retrogressive metamorphism and, in the examples shown in the diagram, almandine garnet has retrogressed to chlorite and andalusite has reverted to pyrophyllite. Some of the metamorphic textures and features shown in the diagram are illustrated in the photomicrographs in Fig. 14 and correlate with macroscopic structures encountered in the New Consort Mine — Eureka syncline areas (see Figs. 6 and 9).*

Figure 14 : *Photomicrographs of metamorphic fabrics in deformed volcano-sedimentary sequences occurring in the northern section of the Barberton greenstone belt (after Anhaeusser, 1969b). (a) Synkinematic ellipsoidal almandine garnet porphyroblast aligned with hornblende crystals in an amphibolite schist. (b) Boudinaged andalusite porphyroblast in siliceous, aluminous, quartz-mica schists. Pyrophyllite is developed in a tension zone in the centre of the andalusite boudin. The S1 fabric of the quartz-mica schists displays S2 crenulations. (c) Biotite blades and laths folded during F3 deformation (see Fig. 13). (d) Synkinematic andalusite porphyroblast containing biotite, magnetite and quartz (the inclusions form S-trails within the porphyroblast). The andalusite crystal was rotated during F3 deformation and quartz pressure shadows are evident. (e) Matted sillimanite folded by F3 deformation. (f) Muscovite schists, buckled by early stages of folding (see Fig. 13), displaying evidence of post-kinematic recrystallization (tabular muscovite crystal superimposed over earlier-formed bladed crystals). (g) Poikiloblastic garnet porphyroblast (displaying micro joints and quartz inclusions) formed as a post-kinematic mineral in crenulated quartz-sillimanite-biotite schists. (h) Blades and radiating clusters of chloritoid formed as post-kinematic overgrowth minerals superimposed on pyrophyllite-sericite-quartz schists that also contain some rutile and staurolite. (i) Typical late phase (F4) kink-band folding in quartz-sericite schists. (j) Poikiloblastic almandine garnet porphyroblast with aligned helicitic quartz inclusions, developed during an early state of metamorphism, exhibiting signs of rotation as a result of late stage deformation. Scale — 3 cm on photographs approximately equivalent to 1 mm in thin section.*

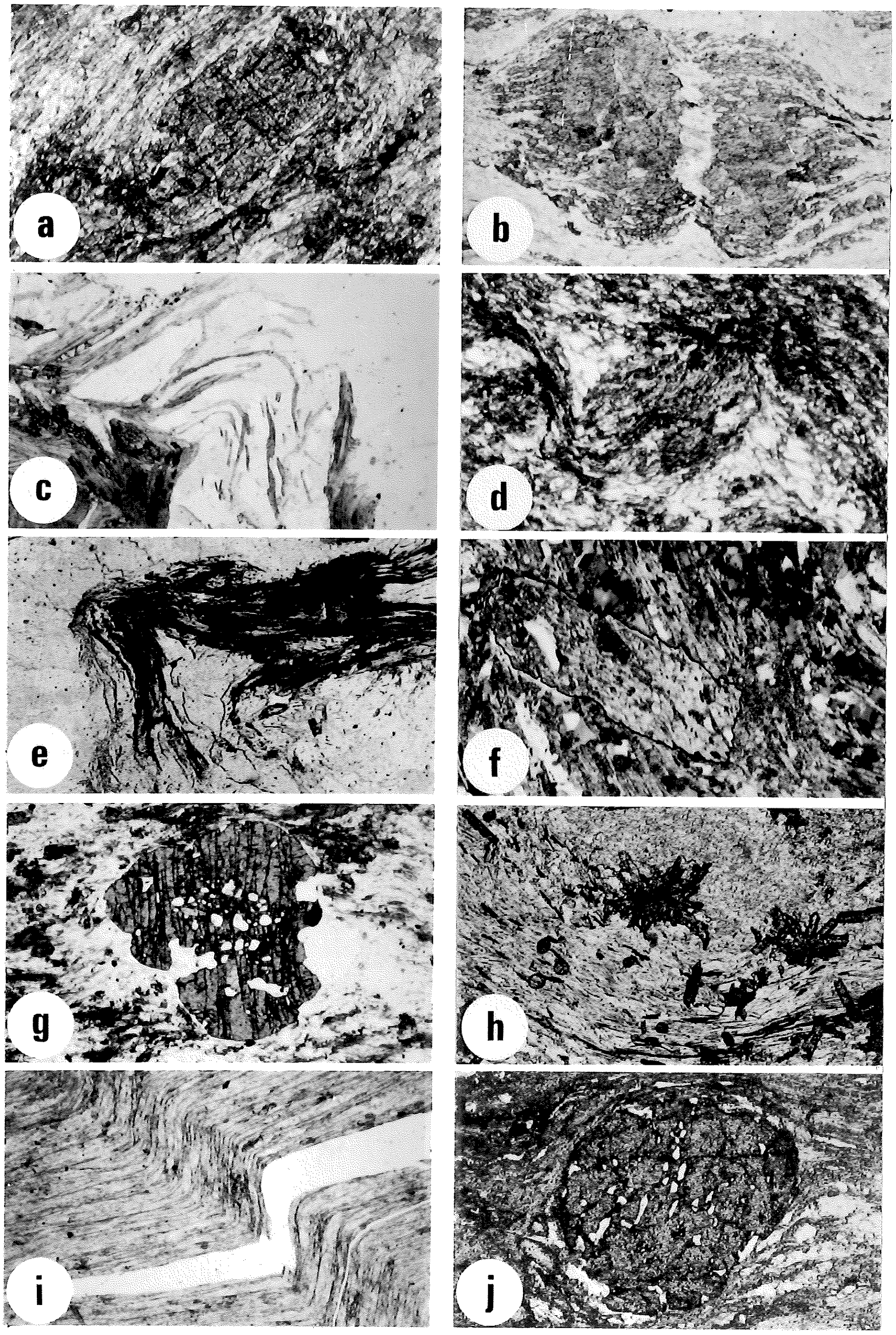


Figure 14 : *See explanation to Fig. 14 on facing page*

superimposed tectonic influences, such as those accompanying diapirism, can produce identical fabrics. Therefore, assessment of the structural and metamorphic history of a region requires close consideration of both field and petrographic data.

Following the initial deformation, superimposed tectonic influences (often diapir-related) may result in F2, F3 --- F*n* phases of deformation. Accompanying each successive structural event there may also be associated metamorphic events involving porphyroblastesis, the latter followed by crenulation or shearing to produce microfolds, boudins, and rotated structures (Figs. 13 and 14). One or more stages of mineral development and recrystallization may occur, depending upon the structural stability of the region. Finally, retrogressive metamorphism signals the end of tectono-thermal activity as may be witnessed in the example (Fig. 13) where garnets retrogress to chlorite and andalusite to pyrophyllite.

V. DISCUSSION

Granite-greenstone terranes exhibit a wide range of structural and metamorphic features. These may be seen to occur at scales ranging from subcratonic to sub-microscopic dimensions.

The gravitational instability of the Archaean crust (either ensialic or ensimatic) was probably the dominant tectonic factor influencing granite-greenstone evolution. The possibility that compressive strains were operative in the Archaean environments cannot, however, be ruled out. If some form of modified plate tectonic process did occur during the early history of the earth this must almost certainly have been accompanied by regional compressive forces. Primitive subduction zones and density inversion may have led to the foundering of lithospheric slabs (Anhaeusser, 1975) and the ultimate production of granitic magmas by the partial melting of metavolcanic rocks at depth. These granitic bodies rose diapirically, thereby initiating protocontinental growth and accretion. The emplacement of the granitic plutons was accompanidd by widespread fragmentation, assimilation, and metamorphism of the supracrustal volcano-sedimentary successions. In addition, granitic diapirism was largely responsible for the generation of almost the entire range of structural features illustrated in this contribution. However, in some Archaean granite-greenstone environments it has been argued that diapirism alone has not determined the structural sequence but that an interplay between the rise of granitic bodies and regional horizontal stresses, including post-granite horizontal crustal shortening and elongation, as well as shortening strain caused by shear zone displacements, were important contributory factors (Coward and James, 1974; Coward *et al.*, 1976; Fyson, 1978; Fripp *et al.*, 1980; Platt, 1980; Park, 1981; De Wit, 1982).

ACKNOWLEDGMENTS

I am grateful to M.P.A. Jackson and M.J. Bickle for their constructive criticism and comments which helped improve an early version of this paper. C. Roering also offered useful advice and helpful discussion. Mrs. D. Amaler is thanked for having typed draft and final copies of this paper.

REFERENCES

Anhaeusser, C.R. (1966). Facets of the granitic assemblage on the north-west flank of the Barberton Mountain Land. *Inform. Circ. Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg*, 32, 27 pp.

Anhaeusser, C.R. (1969a). A comparison of pebble and fold deformations in the Nelspruit granite contact aureole, Barberton Mountain Land. *Trans. geol. Soc. S. Afr.*, 72, 49-60.

Anhaeusser, C.R. (1969b). *The stratigraphy, structure, and gold mineralization of the Jamestown and Sheba Hills areas of the Barberton Mountain Land.* Ph.D thesis (unpubl.), Univ. Witwatersrand, Johannesburg, 332 pp.

Anhaeusser, C.R. (1972). The geology of the Jamestown Hills area of the Barberton Mountain Land, South Africa. *Trans. geol. Soc. S. Afr.*, 75, 225-263.

Anhaeusser, C.R. (1975). Precambrian tectonic environments. *Ann. Rev. Earth Planet. Sci.*, 3, 31-53.

Anhaeusser, C.R. (1976). The geology of the Sheba Hills area of the Barberton Mountain Land, South Africa, with particular reference to the Eureka syncline. *Trans. geol. Soc. S. Afr.*, 79, 253-280.

Anhaeusser, C.R. (1980). A geological investigation of the Archaean granite-greenstone terrane south of the Boesmanskop syenite pluton, Barberton Mountain Land. *Trans. geol. Soc. S. Afr.*, 83, 93-106.

Anhaeusser, C.R., and Robb, L.J. (1980). Regional and detailed field and geochemical studies of Archean trondhjemitic gneisses, migmatites and greenstone xenoliths in the southern part of the Barberton Mountain Land, South Africa. *Precambrian Res.*, 11, 373-397.

Anhaeusser, C.R., Roering, C., Viljoen, M.J., and Viljoen, R.P. (1968). The Barberton Mountain Land: a model of the elements and evolution of an Archaean fold belt. *Annex. Trans. geol. Soc. S. Afr.*, 71, 225-253.

Anhaeusser, C.R., Mason, R., Viljoen, M.J., and Viljoen, R.P. (1969). A reappraisal of some aspects of Precambrian shield geology. *Bull. geol. Soc. Amer.*, 80, 2175-2200.

Anhaeusser, C.R., Robb, L.J., and Viljoen, M.J. (1983). Notes on the provisional geological map of the Barberton greenstone belt and surrounding granitic terrane, Eastern Transvaal and Swaziland (1:250 000 colour map). *Spec. Publ. geol. Soc. S. Afr.*, 9, 221-223.

Borradaile, G.J. (1982). Comparison of Archean structural styles in two belts of the Canadian Superior Province. *Precambrian Res.*, 19, 179-189.

Clifford, P.M. (1972). Behaviour of an Archean granitic batholith. *Can. J. Earth Sci.*, 9, 71-77.

Coomer, P.G., Coward, M.P., and Lintern, B.C. (1977). Stratigraphy, structure and geochronology of ore leads in the Matsitama schist belt of northern Botswana. *Precambrian Res.*, 5, 23-41.

Coward, M.P., and James, P.R. (1974). The deformation patterns of two Archaean greenstone belts in Rhodesia and Botswana. *Precambrian Res.*, 1, 235-258.

Coward, M.P., James, P.R., and Wright, L.I. (1976). Northern margin of the Limpopo mobile belt, southern Africa. *Bull. geol. Soc. Amer.*, 87, 601-611.

Davidson, D.M. (1980). Emplacement and deformation of the Archean Saganaga batholith, Vermilion District, Northeastern Minnesota. *Tectonophysics*, 66, 179-195.

De Wit, M.J. (1982). Gliding and overthrust nappe tectonics in the Barberton greenstone belt. *J. Structural Geol.*, 4(2), 117-136.

De Wit, M.J., Fripp, R.E.P., and Stanistreet, I.G. (1983). Tectonic and stratigraphic implications of new field observations along the southern part of the Barberton greenstone belt. *Spec. Publ. geol. Soc. S. Afr.*, 9, 21-29.

Drury, S.A. (1977). Structures induced by granite diapirs in the Archaean greenstone belt at Yellowknife, Canada: Implications for Archaean geotectonics. *J. Geol.*, 85, 345-358.

Ehlers, C. (1978). Gravity-induced tectonics and deformation in the Kumlinge area, SW Finland. *Acta Academiae Aboensis, Ser. B.*, 38(2), 1-7.

Fripp, R.E.P., van Nierop, D.A., Callow, M.J., Lilly, P.A., and du Plessis, L.U. (1980). Deformation in part of the Archaean Kaapvaal craton, South Africa. *Precambrian Res.*, 13, 241-251.

Fyson, W.K. (1978). Structures induced by granite diapirs in the Archaean greenstone belt at Yellowknife, Canada: Implications for Archaean geotectonics: A discussion. *J. Geol.*, 86, 767-779.

Fyson, W.K., Herd, R.K., and Ermanovics, I.F. (1978). Diapiric structures and regional compression in an Archean greenstone belt, Island Lake, Manitoba. *Can. J. Earth Sci.*, 15, 1817-1825.

Gay, N.C. (1969). The analysis of strain in the Barberton Mountain Land, Eastern Transvaal, using deformed pebbles. *J. Geol.*, 77, 377-396.

Gorman, B.E., Pearce, T.H., and Birkett, T.C. (1978). On the structure of Archaean greenstone belts. *Precambrian Res.*, 6, 23-41.

Leith, C.K. (1923). *Structural Geology*, New York, 192 pp.

Macgregor, A.M. (1951). Some milestones in the Precambrian of Southern Rhodesia. *Proc. Trans. geol. Soc. S. Afr.*, 54, xxvii-lxxi.

Mason, R., (1973). The Limpopo mobile belt — southern Africa. *Phil. Trans. Roy. Soc. Lond.*, *Ser.* A 273, 463-485.

Myers, J.S. (1978). Formation of banded gneisses by deformation of igneous rocks. *Precambrian Res.*, 6, 43-64.

Park, R.G. (1981). Shear-zone deformation and bulk strain in granite-greenstone terrain of the Western Superior Province, Canada. *Precambrian Res.*, 14, 31.47.

Platt, J.P. (1980). Archaean greenstone belts: a structural test of tectonic hypotheses. *Tectonophysics*, 65, 127-150.

Ramberg, H. (1973). Model studies of gravity-controlled tectonics by the centrifuge technique. In: De Jong, K.A., and Scholten, R. (Eds.), *Gravity and Tectonics*, John Wiley, New York, 49-66.

Ramberg, H. (1981). *Gravity, Deformation, and the Earth's Crust.* Academic Press, London, 452 pp.

Ramsay, J.G. (1962). Interference patterns produced by the superimposition of folds of similar type. *J. Geol.* 70, 466-481.

Ramsay, J.G. (1963). Structural investigations in the Barberton Mountain Land, Eastern Transvaal. *Trans. geol. Soc. S. Afr.*, 66, 353-401.

Robb, L.J. (1983). The nature, origin and significance of Archaean migmatites in the Barberton Mountain Land; a new approach in the assessment of early crustal evolution. *Spec. Publ. geol. Soc. S. Afr.*, 9, 81-101.

Schwerdtner, W.M., Stone, D., Osadetz, K., Morgan, J., and Stott, G.M. (1979). Granitoid complexes and the Archean tectonic record in the southern part of northwestern Ontario. *Can. J. Earth Sci.*, 16, 1965-1977.

Schwerdtner, W.M., Sutcliffe, R.H., and Tröeng, B. (1978). Patterns of total strain in the crestal region of immature diapirs. *Can. J. Earth Sci.*, 15. 1437-1447.

Sorgenfrei, T. (1971). On the granite problem and the similarity of salt and granite structures. *Geol. Foren. Stockholm Forh.*, 93, 371.435.

Stephansson, O. (1975). Polydiapirism of granitic rocks in the Svecofennian of Central Sweden. *Precambrian Res.*, 2, 189-214.

Stephansson, O. (1977). Granite diapirism in Archaean rocks. *J. geol. Soc. Lond.*, 133, 357-361.

Stowe, C.W. (1974). Alpine-type structures in the Rhodesian basement complex at Selukwe. *J. Geol. Soc. Lond.*, 130, 411-425.

Viljoen, M.J. (1963). *The geology of the Lily syncline and portion of the Eureka syncline between the Consort mine and Joe's Luck siding, Barberton Mountain Land.* M.Sc. thesis (unpubl.), Univ. Witwatersrand, Johannesburg, 131 pp.

Viljoen, R.P., Viljoen, M.J. Grootenboer, J., and Longshaw, T.G. (1975). ERTS-1 imagery : an appraisal of applications in geology and mineral exploration. *Minerals Sci. Engng.*, 7, 132-168.

Wilson, G. (1961). The tectonic significance of small-scale structures, and their importance to the geologist in the field. *Ann. Soc. Geol. de Belg.*, 84, 423-548.

Wright, L.I. (1975). A deformation study of the Gwanda schist belt and its implications for the formation of the belt. *19th Ann. Rep. Res. Inst. Afr. Geol., Univ. Leeds*, 59-65.

——— oOo ———