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TECTONIC INVESTIGATION OF MASVINGO PROVINCE, ZIMBABWE: PRELIMINARY REPORT

by

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ABSTRACT

This report summarises the preliminary results of a structural investigation in the Masvingo (Victoria) Province of SE Zimbabwe undertaken as part of a hydrogeological study of the occurrence of groundwater in crystalline basement rocks. A review of the tectonic development of the region from available literature is presented together with the initial results of a remote sensing study using Landsat MSS imagery and aerial photographs, as well as reconnaissance fieldwork. The Zimbabwe craton has had a complex tectonic history involving several episodes of ductile to brittle deformation extending back well into the Archaean. From a groundwater viewpoint the brittle deformational events commencing in the Late Archaean at about the time of emplacement of the Younger Granites are considered to be of greatest importance. The fracture patterns noted from past geological mapping and evident on Landsat imagery provide clues to the tectonic history of the region but further field study will be needed to establish age relationships, which cannot be unequivocally decided from remote sensing data alone. Nevertheless, on the basis of available evidence, a possible model of the Late Archaean-Early Proterozoic tectonic development of the region is discussed. This report also considers the problems of using empirical tectonic models in the exploration for groundwater. A follow-up work programme is discussed.

1. INTRODUCTION

The occurrence of groundwater in areas of crystalline basement in Africa and Asia can often be related to the presence of secondary porosity in the form of fractures (Dennis & Hindson 1964; Jordan 1968). Where the regolith has reasonable thickness (10 - 15 metres) and rainfall is moderate, adequate supplies may generally be obtained from within the weathered zone (Chilton & Smith-Carington 1984). However, where the regolith is thin or the water table deep, more attention in siting wells needs to be given to the presence of underlying fracture zones (Buckley & Zeil 1984). As part of a research project to investigate the controls of groundwater occurrence in Zimbabwe a structural study is being carried out over part of the Masvingo (Victoria) Province (approx. Lat 29° 30' to 32°E, 19° 30' to 21°S) (Figure 1). This area corresponds in part to the recent EEC drought-relief project and was the focus of investigations and drilling by both Hydrotechnica (1984; Houston in press; Houston & Lewis in press) and Sanyu Consultants Inc.(1985). This report summarises the preliminary findings of the current research: it comprises a review from the literature of the tectonic development of the southern part of the Zimbabwe craton, and initial conclusions arising out of a remote sensing investigation, involving Landsat imagery, aerial photographs and reconnaissance fieldwork.

2. GENERAL GEOLOGY

The Zimbabwe craton is an Archaean granite-greenstone complex that developed from c. 3500 Ma to c. 2460 Ma ago. It comprises basement schists of the greenstone belts, "Older" granites and gneisses, mafic and ultramafic intrusions, batholithic intrusions of "Younger" granites, and the Great "Dyke". A

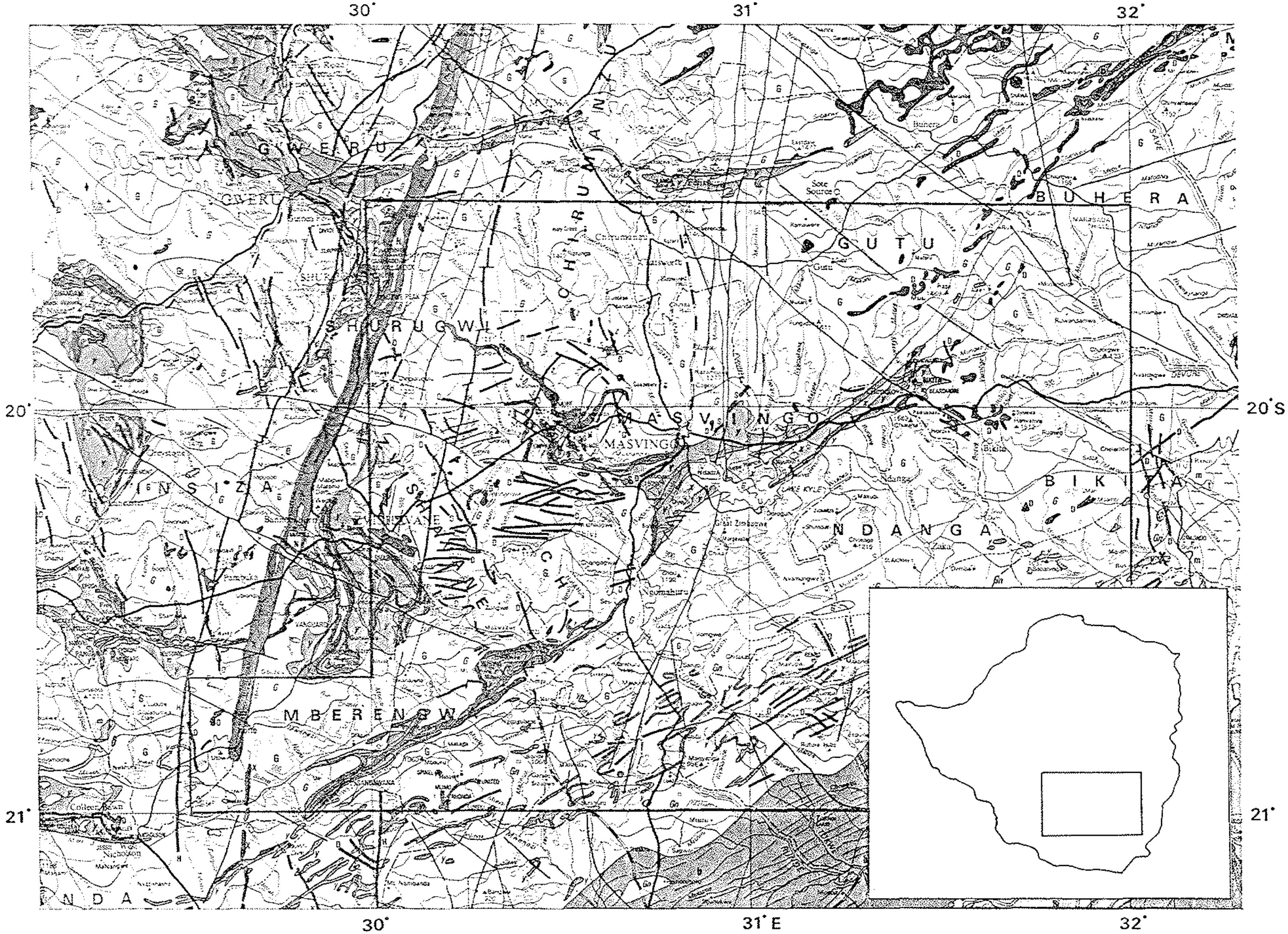


Figure 1: Location and regional geology of the study are.

formal stratigraphy for the greenstones is yet to be agreed. Current nomenclature essentially follows that established by Macgregor (1947, 1951). The greenstone belts are the remnants of volcano-sedimentary piles now represented as synformally folded schist belts provisionally assigned to three ages: the c. 3500 Ma Sebakwian, the c. 2900 Ma Lower Bulawayan and the c. 2700 Ma Upper Bulawayan and locally developed Shamvaian (Figure 2).

The Sebakwian Group consists of metamorphosed arenaceous sediments and mafic volcanics and is confined to a roughly triangular segment of ancient gneissic crust in the Selukwe-Shabani-Masvingo area of south-central Zimbabwe. The gneisses and granites of this area are dominantly tonalitic to granodioritic (Wilson 1973) and have been dated at around 3500 Ma (Wilson 1979). In part these rocks may represent an older pre-Sebakwian sialic basement on which the early greenstones developed (Stowe 1968; Bliss & Stidolph 1969; James 1975; Coward 1976; Coward *et al*. 1976; Wilson, 1979).

The main greenstone belts are separated into two sequences partly by an unconformity and at least one period of deformation. The Lower Bulawayan succession (or Lower Greenstones of Wilson 1979 and Wilson *et al*. in press) consists largely of mafic-felsic volcanic sequenses together with ultramafic rocks, and is provisionally dated at c. 2900 Ma. It is best developed in the Belingwe area. The Upper Bulawayan succession (Upper Greenstones of Wilson *op cit*.) is more widely developed over the craton: it formed on a basement comprising the c. 3500 Ma granite-greenstone terrain, the Lower Bulawayan greenstones and the associated granitic rocks. It contains both tholeiitic and calc-alkali volcanic sequences (Hawkesworth & O'Nions 1977) as well as sedimentary units, and is dated at c. 2700 Ma (Robertson 1973; Wilson 1979). These rocks are unconformably overlain locally by the sedimentary Shamvaian Group.

A number of mafic and ultramafic layered intrusions, sills and

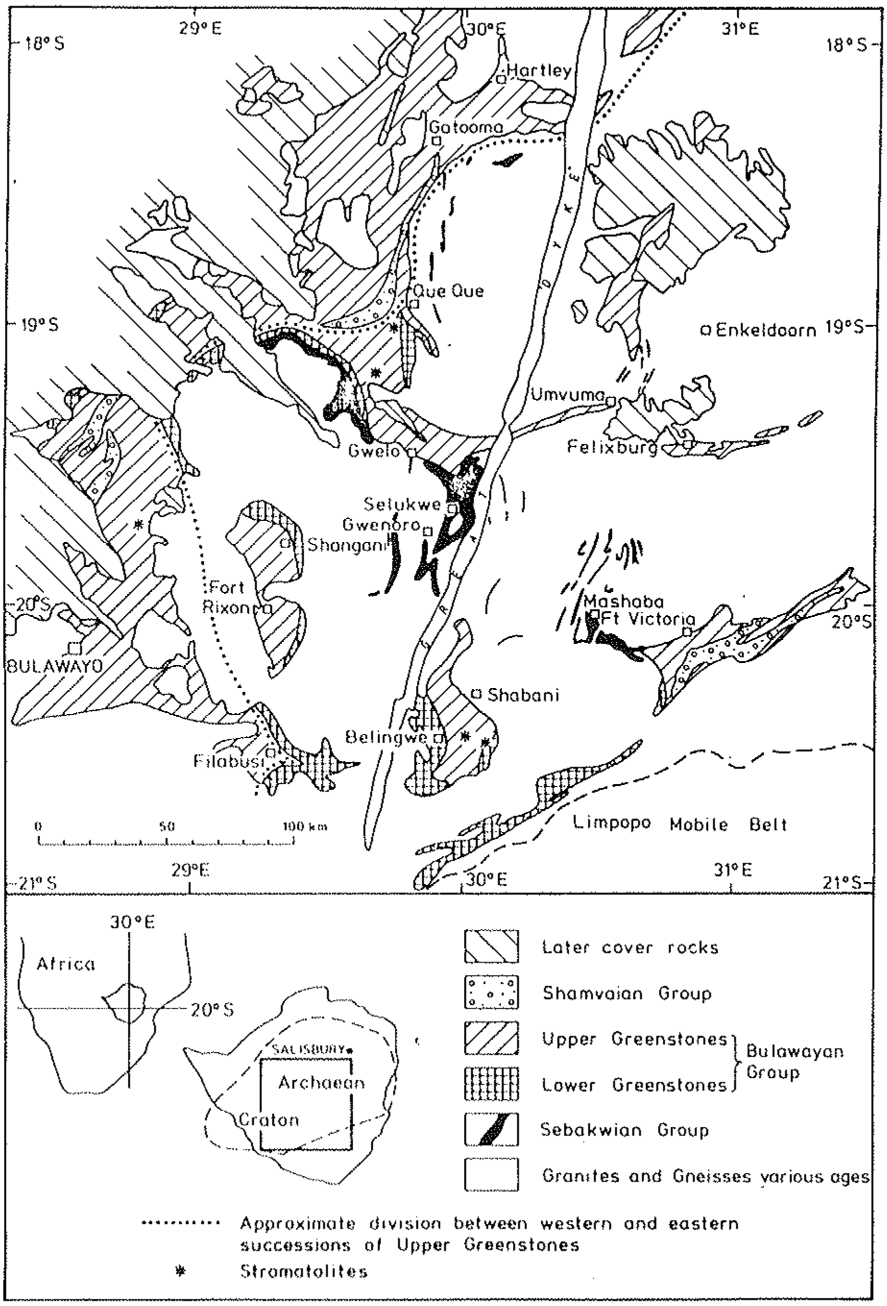


Figure 2: Subdivisions of the greenstone belts in the central area of the Zimbabwe Archaean craton. (From Wilson 1981).

dykes invade the craton. The best documented of these are the layered ultramafic intrusions and dyke swarms of the Mashaba and Shabani area. These cut the Mashaba tonalite (2970 ± 160 Ma) but are older than the Chilimanzi granite (2625 ± 25 Ma) (Wilson 1979).

Emplacment of the "Younger" suite of batholithic granites post-dated the Upper Bulawayan and Shamvaian greenstones. Wilson (1979) recognised two series of granitoid intrusions: an earlier group of tonalitic and granodioritic bodies in the west of the craton typified by the Sesombi and Somabula tonalites, and a slightly later series of massive and porphyritic, high-potash adamellites of the Chilimanzi Suite which make up much of the eastern half of the craton (Figure 3). Emplacement of the "Younger" granites is dated at between 2700 and 2600 Ma.

The end of the Archaean in the Zimbabwe craton is marked by the emplacement of the Great "Dyke" dated at 2460 ± 16 Ma (Hamilton 1977; Wilson *et al*. in press).

To the south, east and north, the craton is bounded by the mobile belts of the Limpopo, Mozambique and Zambezi respectively (Figure 4), representing zones of intense polyphase metamorphism and deformation. The Limpopo Mobile Belt is recognised as a zone of tectonic activity beginning before about 3800 Ma and continuing until about 2600 Ma (Barton 1983a). The Belt comprises three main tectono-stratigraphic domains: a Central Zone of nearly N-S trending folds within a series of high-grade metasediments, paragneisses and intercalated orthogneisses, and the Northern and Southern Marginal Zones of ENE regional fold trends within sheared and mylonitised granulites, representing the reworked granite-greenstone successions of the adjacent cratons (Cox *et al*. 1965; Mason 1973; James 1975; Barton 1983b). Within Zimbabwe the Northern Marginal Zone would appear to represent a wide ductile shear zone thrust at low angle NNW onto the granites and greenstones of the craton (James 1975). Deformation within

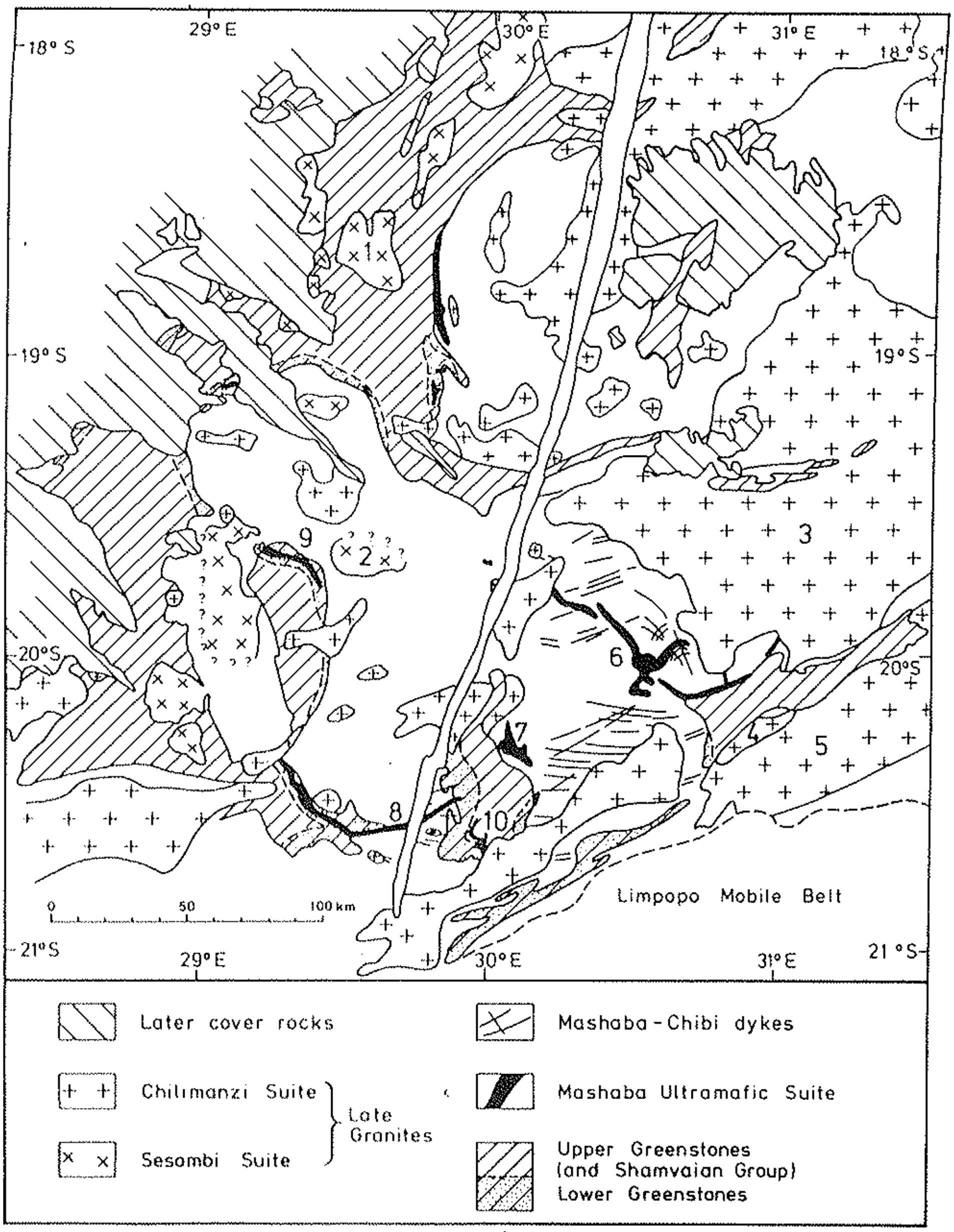


Figure 3: Distribution of the Younger Granites, Mashaba-Chibi dykes and Mashaba Ultramafic Suite in the central cratonic area. 1 = Sesombi tonalite; 2 = Somabula tonalite; 3 = Chilimamanzi batholith; 4 = Victoria Porphyritic granite; 5 = Zimbabwe batholith; 6 = Mashaba Igneous Complex; 7 = Shabani intrusion; 8 = Gurumbatumba-Filabusi intrusion. (From Wilson 1981).

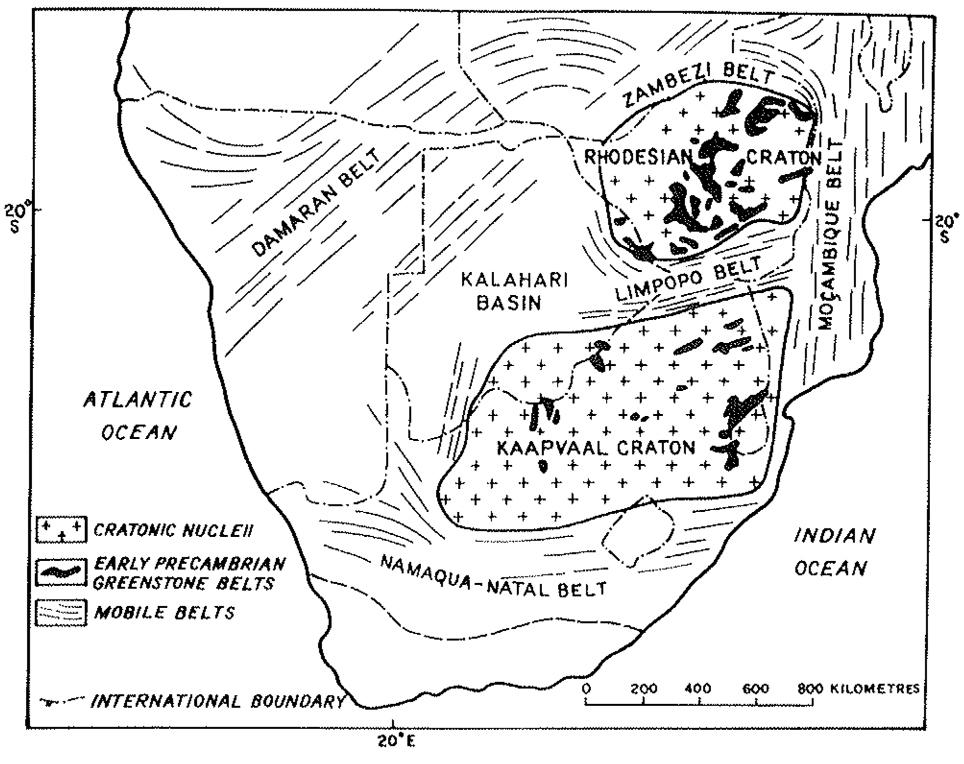


Figure 4: The Limpopo Mobile Belt and other metamorphic belts of southern Africa. (From Robertson et al. 1981).

this zone and the adjacent craton is discussed more fully later.

The last deformation of the Mocambique and Zambezi mobile belts is Pan-African (c. 600 - 500 Ma) but both are evidently polymetamorphic and polytectonic and appear to have begun their development during the Proterozoic. The Zambezi Belt has been shown to have overprinted metamorphic events at c. 2300 - 2100 Ma, 1900 - 1650 Ma, 1300 - 1100 Ma and 600 - 400 Ma (Holmes & Cahen 1957; Vail 1965). The Umkondo Group, of probable middle Proterozoic age, was thrust westwards during the Mozambique deformation.

In the west the rocks of the craton are overlain by the Proterozoic Deweras, Lomagundi and Piriwiri Groups, Karroo (Permian to Jurassic) sediments and volcanics, and by Tertiary Kalahari sands.

The Zimbabwe craton and adjoining areas have thus suffered a long and complex tectonic history which is still incompletely known: this is reviewed below. Most research to date has concentrated on the early ductile and semi-ductile events that preceded the emplacement of the Younger Granites. Less is known of the mainly brittle deformation events that occurred subsequently and are of greater significance from a groundwater viewpoint.

3. ARCHAEAN DEFORMATION OF THE LIMPOPO MOBILE BELT & ZIMBABWE CRATON

Archaean deformation of the Limpopo Mobile Belt and Zimbabwe craton has been studied in some detail by Coward and co-researchers (Coward *et al.* 1973; Coward & James 1974; James 1975; Coward 1976; Coward *et al.* 1976; Coward 1983). The Northern Marginal Zone appears to have had a similar early history to adjoining parts of the Zimbabwe craton and did not form a separate entity until the Late Archaean (Tankard et al. 1982); structural and metamorphic events during this period extended at least 120 km northwards into the craton (Coward et al. 1973; Coward 1976). In the high grade metamorphic terrain of the Limpopo Belt, and at deeper crustal levels within the craton, ductile deformation formed the dominant mechanism. At higher levels in the craton or as the thermo-tectonic regime that dominated the Archaean wained and the craton stabilised, stresses were relieved through semi-ductile shearing and brittle failure. Coward identified at least four major deformation phases (F_1 to F_4) which vary in form and intensity across the region (Figure 5):

1. An early pre-cleavage regional deformation (F_1) which affected both the Zimbabwe craton and the Limpopo Belt.

2. An important regional penetrative tectonite fabric (F_2). This shows a marked heterogeneity of development over the area leading to the formation of discrete areas of high and low intensity fabric (James 1975).

3. In SW Zimbabwe and N Botswana steeply dipping superimposed crenulation cleavage or mylonitic fabric (F_3).

4. In Zimbabwe F_4 structures are a series of shear zones and folds that are cut by the Great "Dyke". (Other F_4 structures in Botswana and the Transvaal may be of a different age).

The dating of these deformation events is not well constrained and the fabrics may not have been synchronous in all parts of the region. F_1 may have commenced prior to about 2900 Ma, or possibly much earlier, but F_2 to F_4 appear to be bracketed within a comparatively short time interval during the Late Archaean.

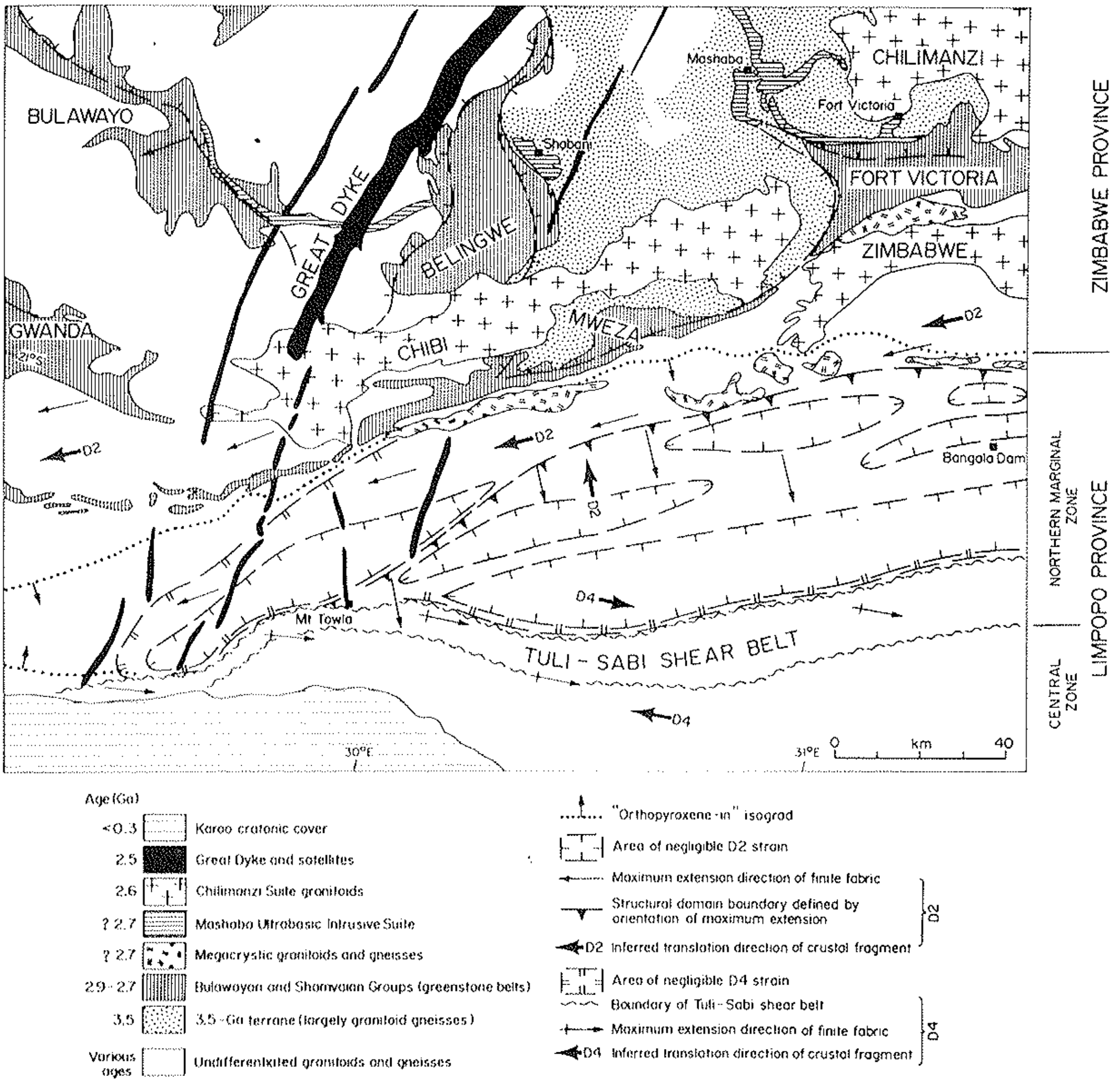


Figure 5: Relations between structural domains of various ages, inferred directions of crustal translation and the orthopyroxene isograd in the Northern Marginal Zone and the contiguous Zimbabwe craton. (From Tankard et al. 1982).

F_1 DEFORMATION

Geological mapping of the greenstone belts has provided evidence of several phases of Archaean deformation prior to the penetrative F_2 event (e.g. Stowe 1968; Wilson 1968; Martin 1978). Thus, whereas the final phase of F_1 deformation apparently occurred later than about 2700 Ma, since it involved folding of the Lower and Upper Bulawayan together with the Shamvaian sediments, F_1 folding was evidently a polydeformational event on the craton (Coward _et al_. 1976; Wilson 1979) which spanned a considerable interval of time extending back to the Sebakwian. In the Northern Marginal Zone of the Limpopo Belt, the F_1 event appears to have preceded a widespread metamorphism and intrusion at about 2900 Ma (Hickman 1978; Tankard _et al_. 1982). The tectonic style of F_1 is highly variable but is generally characterised by major upright folds in both high and low grade metamorphic terrains.

In the Selukwe area the Sebakwian succession is overturned and forms the lower limb of a large recumbent fold (the Selukwe Nappe (Stowe 1968; Cotterill 1979) which was deformed at least twice prior to F_2. The Wanderer Formation at the base of the upper sequence here lies unconformably on a folded and eroded lower sequence. The Nappe is apparently intruded by the c. 3420 $\pm$ 120 Ma Mont d'Or tonalite which places an upper limit on this deformation event. Both the Shabani-Belingwe and the Bulawayo greenstone belts were folded into major synclines before the F_2 cleavage which cuts across the bedding in the fold limbs (Coward _et al_. 1976). According to Wilson (1981) this involved at least two deformation events, the Lower Greenstones having been deformed and eroded prior to the deposition of the Upper Greenstones. The Antelope and Lower Gwanda belts are associated with allochthonous basement gneisses thrust over the greenstones (Coward, Lintern & Wright 1976). Further to the west the greenstones of the Tati are overturned and may be correlated with similar sequences to the north at Vumba to make an extensive sheet of overturned NE-facing rocks (Litherland & Key 1974; Coward 1976). This again pre-dated the intrusion of the Younger diapiric granites and the main F_2 cleavage. Similar overturned rocks occur in the core of the Matsitama belt still further west. Thus, Coward (1976) concluded that many of the greenstone and gneiss sequences in the southwest were allochthonous and that the early deformation took place by bulk translation and rotation. The Bulawayo, Shabani-Belingwe and Masvingo belts appear to be autochthonous, and the succession at Shabani-Belingwe rests directly on older gneisses, but these too suffered considerable deformation before and possibly during intrusion of the diapiric granites. However, despite the views of Anhaeusser et al. (1969; Anhaeusser 1973) and Mason (1973), who considered that much of the greenstone deformation was caused by the forceful intrusion of granite, many of these granites clearly post-date the overturning of the Tati/Vumba belts (Litherland & Key 1974; Coward & James 1974) and at Bulawayo and Masvingo the granite post-dates folds in the autochthonous greenstones (Coward 1976).

F_2 DEFORMATION

The age of the important F_2 deformation event can be bracketed between the Upper Bulawayan/Shamvaian greenstones (c. 2700 Ma), both of which show F_2 deformation, and certain post-tectonic granites of the Chilimanzi Suite (c. 2600 Ma). James (1975) noted that the F_2 fabric in one shear belt cuts obliquely across major apophyses of homogeneous granite mapped by Robertson (1974) as part of the main Zimbabwe batholith. An upper age limit for the F_2 event of c. 2460 Ma is given by the Great "Dyke" satellites which cut the granulite terrain of the Northern Marginal Zone and even transect F_4 structures. To the south of the Buchwa-Masvingo greenstone belt within the granulites of the Northern Marginal Zone, sheetlike bodies of "Younger" porphyritic granites dipping south are strongly deformed by F_2 fabrics (Robertson 1973). These syntectonic granites thus predate the

Chibi, Zimbabwe and Masvingo Porphyritic granites which are post-tectonic and cut across the F_2 structures in the Belingwe greenstone belt (Tankard et al. 1982). The Chibi batholith together with the Chilimanzi and Zimbabwe batholiths constitute the Chilimanzi Suite dated at c. 2600 Ma.

Coward et al. (1976) divided the region into four post-F_1 structural domains, within each of which the structural fabric showed a consistency of relations (Figure 6). Within Domain 1, comprising the southern half of the Zimbabwe craton, the rocks consist of Archaean granites and greenstones and the fabric is characterised by an arcuate pattern of foliation (schistosity or cleavage) but a constant SSE trend of the penetrative F_2 linear structures, as shown by the preferred orientation of minerals and deformed grains and inclusions (Coward & James 1974; James 1975; Coward et al. 1976; Coward 1983). Major shear zones cut across the foliation and in the southern part of the domain have a NE trend, a sinistral sense of movement and a nearly horizontal maximum extension direction. Coward et al. (1976) considered that this regional deformation pattern indicated movement of the Zimbabwe craton to the SW relative to the Limpopo Belt and, using an estimate of 49% mean shortening in the SW area, estimated a maximum movement of some 200 km. Bodies of granite and gneiss within the craton responded to F_2 deformation in different ways. While some deformed homogeneously with the gneisses or greenstones, others remained as competent bodies: the term "billiard-ball tectonics" was coined to describe this phenomenon (Coward & James 1974) whereby many of the granite units moved against one another by sliding along block boundaries.

Domain 2 consists of sheared and mylonitised granulite facies rocks comprising the Northern Marginal Zone of the Limpopo Mobile Belt. The age of the crust that suffered granulite facies metamorphism is uncertain. Tankard et al. (1982) favoured an analogy with the c. 2900 Ma terrain of the craton represented by the Chingezi gneisses, the Lower Bulawayan greenstones and the

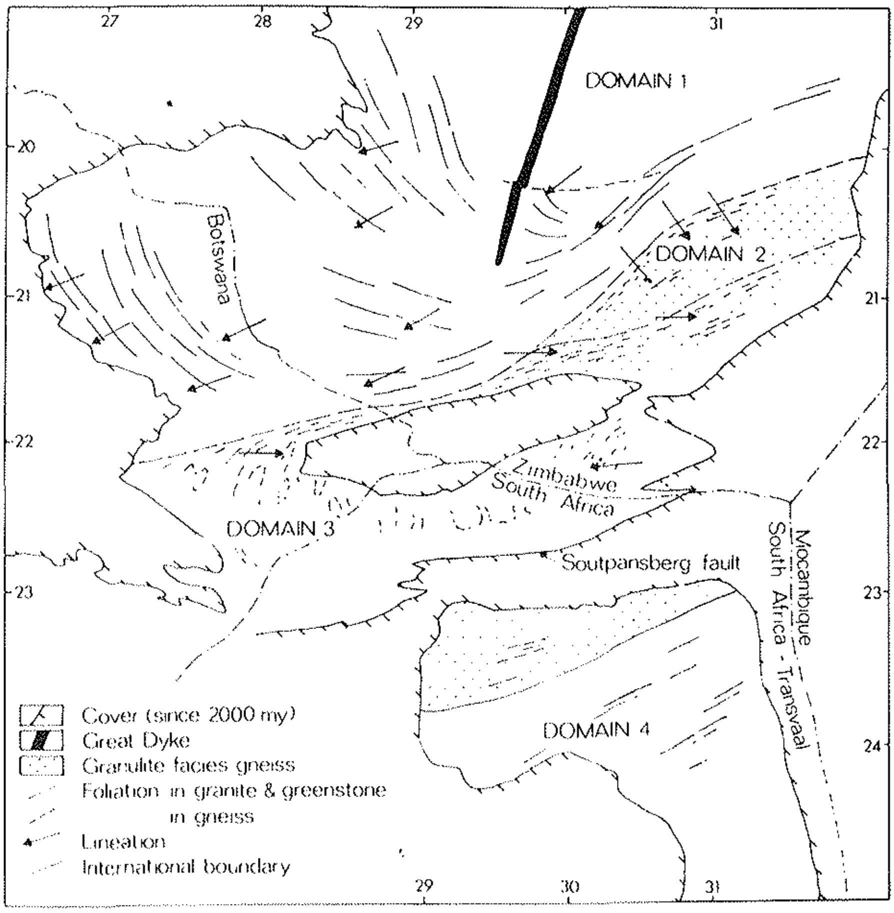


Figure 6: Structural domains in Zimbabwe, Botswana and South Africa. The different domains are identified by their different dominant movement directions as deduced from extension directions and sheath folds in shear zones. (From Coward & Daly 1984).

Mashaba tonalite. They noted that near Bangala Dam granulite gneiss which escaped penetrative deformation during F_2 yielded a date of 2870 ± 60 Ma. Much of the Northern Marginal Zone shows negligible F_2 strain but is crossed by several shear zones, apparently produced during F_2, and the northern limit is marked by a major ENE-trending, southerly-dipping shear zone. The lineation on these shears dominantly plunges to the SSE and James (1975) considered that the the granulites in this domain had been thrust from the SSE along these moderately dipping shear zones. Thus, it would seem major uplift and northnorthwestward transport of the granulites took place along a basal shear at their northern margin and also along similar discontinuities within this zone, possibly by penetrative ductile simple shear (James 1975; Tankard _et al_. 1982). James (1975) also noted the presence of semi-ductile and ductile conjugate shears which periodically offset the thrust at the northern margin of the granulites. Their association with the foliation suggested formation during F_2. He considered that the maximum principal stress responsible for the formation of both the main F_2 fabric and the conjugate shears was orientated NNW-SSE.

POST-F_2 DEFORMATION

The F_3 event , forming sporadic crenulation or mylonitic fabrics elsewhere, left no trace in the Northern Marginal Zone (Coward _et al_. 1976). However, large-scale F_4 movements occurred along the southern edge of this zone. The northern margin of Domain 3 is marked by a shear zone (Tuli-Sabi shear belt) (Figure 5) which westwards crosscuts the boundary between Domains 1 and 2. In the east this zone consists of gently dipping mylonites while in the west, in Botswana, it is steeply dipping. The linear fabric developed in the shear is nearly horizontal and trends eastwards. From this lineation and the curvature of the foliation into the shear zones the movement is inferred to be dextral with a slight up-dip slip component suggesting that the Central zone moved westwards over the Northern Marginal Zone (Coward et al. 1973; Coward 1976). Strain measurements gave an estimate of upto 50 km displacement across this zone in Zimbabwe (Coward 1976; Coward et al 1976). Upright folds with axes trending NNE found further south in the Central Zone but which are absent in Domain 2 suggest that the marginal shear acted as a plane of decollement.

4. LATE ARCHAEAN SHEAR TECTONICS ON THE CRATON (after STOWE 1980)

For the Late Archaean Stowe (1980) recognised four separate systems of semi-ductile and brittle, faulting and shearing prior to emplacement of the Great "Dyke". Stowe's dating of these events is, however, difficult to correlate precisely with the events identified by Coward and co-workers as described above. Stowe's descriptions seem to indicate that they occurred during the latter stages of, or subsequent to, F_2.

System A was recognised as a number of semi-ductile and brittle shear zones in central and southeast parts of the craton. These structures consist of linear or sinuous shear zones and barren quartz veins infilling fractures, and show both dextral and sinistral displacements. The shear zones were noted in places to cut, but elsewhere to be at least partly synchronous with, the emplacement of late granite stocks of the Chilimanzi suite. Stowe considered that the structures could be explained in terms of a pure shear translational model, yet he interpreted the main shearing directions as dextral and sinistral Riedel shears usually considered to form during simple shear (Tchalenko & Ambraseys 1970; Wilcox et al. 1973; Jaroszewski 1984). He inferred a maximum horizontal principal stress axis orientated at about 068^{o}, and suggested that this might correlate with the NW-trending broad open folding of the Chinamora granite (Snowden &

Bickle 1976), the NW open fold in Limpopo Mobile Belt (Bahnemann 1971), the F_3 fabric of Coward _et al_. (1976) and the F_4 folds of Light _et al_. (1977). However, the sense of shearing and of the inferred maximum stress would seem to equate better with Coward's F_2 event and the associated inferred southwesterly movement of the craton (Figure 7A).

System B of Stowe (1980) was detected mainly in the central sector of the craton in the area to the north of Que Que where early shear zones of System A are displaced by complicated, curved semi-ductile and brittle, dextral and sinistral splay faults. Some of these faults displace late granites and Stowe inferred that this faulting corresponded to a late sustained stress from System A with a different orientation of the maximum principal stress now at approximately 015^o (Figure 7B). He considered it to be associated with the final stage of granite emplacement. He suggested it might be equivalent to the ENE-trending conical folds of Light's F_5 event in the Limpopo Belt.

During Stowe's _System C_, the craton was fractured on NW dextral and NE sinistral fault zones marked by refoliation, barren ("buck") quartz veins, silicification and alteration, although it was not everywhere separable from the fractures of System B. This system of fissures seems to correlate to a large extent with a number of vein and fissure gold deposits. Stowe refers to the mainly dextral wrench braided system near Que Que, the relationship between gold mineralisation and shears in the Battlefields area (Robertson 1976), and the system of northerly tensional fissures and ENE sinistral shears in the Selukwe area. He concluded that System C formed under a 020^o horizontal maximum compression (Figure 7C). A problem raised by the comparatively late age assigned by Stowe to the gold-bearing fissures is that these are thereby considered to post-date the main phase of granite intrusion, whereas Foster _et al_. (in press) give an age of 2700 Ma to the Selukwe gold deposits which would correlate

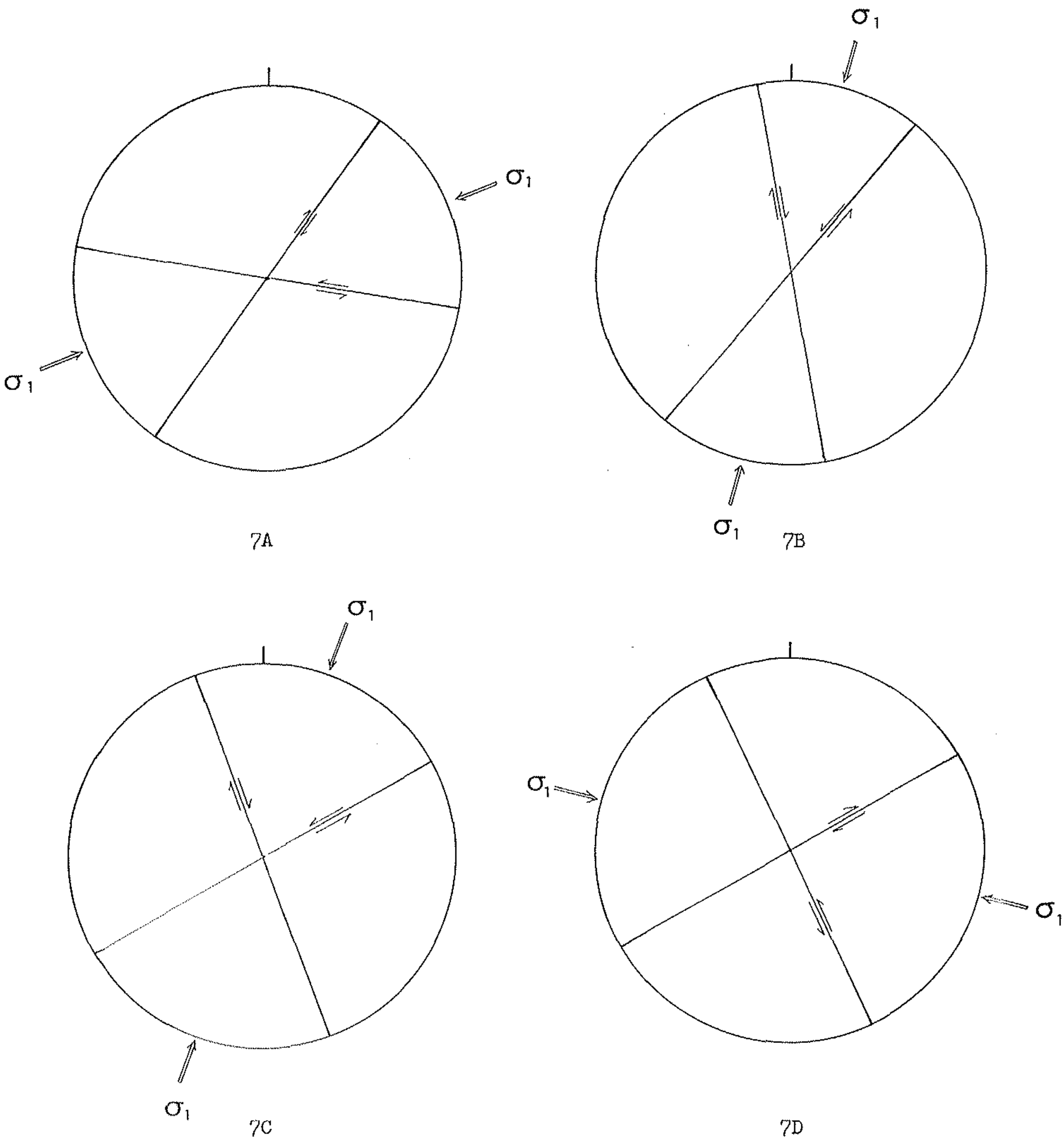


Figure 7: Summary of pre Great "Dyke" semi-ductile and brittle deformation on the Zimbabwe craton according to Stowe (1980). 7A - maximum horizontal stress at 68°; 7B - maximum horizontal stress at 15°; 7C - maximum horizontal stress at 20°; 7D - maximum horizontal stress at 105°.

with emplacement of the Sesombi suite. Nevertheless, the gold veins occupying the Surprise Fault zone - which parallels the Great "Dyke" and is inferred to be late - are apparently somewhat younger and this raises the possibility that so too are some or all of the other deposits.

Under System D, Stowe (op cit.) described an elaborate pattern of dextral wrench faults which margin and transect the craton. He referred to dextral shear zones along the margins of the Gwanda and Tati greenstone belts which Coward et al. (1976) related to the F_3 deformation event, and to dextral shears of possibly similar age cutting the Masvino greenstone belt (Coward & James 1974). Stowe suggested that movement occurred on suitably orientated pre-existing shear zones, in some cases reversing earlier sinistral movements. He noted that new fractures, often curved, splayed off the Northern Marginal Zone of the Limpopo Belt on approximately 290° and resemble the convergent wrench tectonic system described by Wilcox et al. (1973). Stowe ascribed this fracturing to a horizontal maximum principal stress orientated approximately 285° (Figure 7D), and considered the predominance of dextral shears to be due to rotational simple shear, unlike his earlier three wrench systems. In general, however, Stowe provided little supportive evidence for the craton-wide system of dextral shears he described. Interestingly, Watkeys (unpublished manuscript c. 1979) interpreted many of the dextral shears shown by Stowe to have a sinistral movement.

5. LATE ARCHAEAN-EARLY PROTEROZOIC BRITTLE DEFORMATION

Both the analysis of Landsat imagery and available geological maps indicate that the craton has undergone several episodes of syn- and post-granite brittle deformation. Many of these deformation and/or intrusive events can be assigned to the period Late Archaean-Early Proterozoic, roughly from about 2600 Ma to about 1800 Ma, with yet other important events continuing into the Phanerozoic (e.g. Karroo events). A valuable lineament interpretation of the northern two-thirds of Zimbabwe (as far south as latitude 20^{o}) was carried out by Made (1981), and indicates the presence of many new structures and the extension of known ones. The present investigation has extended this interpretation further to the southeast. A simplified lineament map showing the main directions of crustal fracturing in this area is given in Figure 8. An index map to Landsats 4 and 5 is shown in Figure 9. The study area is largely covered by scenes 169-74 and 170-74.

The sequential dating of fractures (used throughout as a general term for all manner of brittle dislocations in rocks, including joints and faults) and dykes is beset with problems that generally cannot be resolved using remote sensing data alone. Thus, for example, the offset of one fracture trace against another is open to several interpretations: (i) the offset fracture could be the displaced older direction, (ii) the offset fracture could be the younger, having been refracted along the pre-existing fracture, or (iii) both could be contemporaneous and represent a conjugate set. Similar considerations apply to dykes displaced by faults: here, the fault could be either younger or the dyke emplaced in discrete segments along a pre-existing, already faulted fissure. In some instances, the sense of movement between two directions of fracturing may show apparently conflicting relationships. This may result from either contemporaneous movements within a conjugate set or reactivation of an earlier fracture direction under new stress conditions.

For the reasons outlined it is not therefore possible at the present stage of the study to uneqivocally define the sequence of fracturing events in the Zimbabwe craton. The following should be regarded as a tentative scheme of events pending further

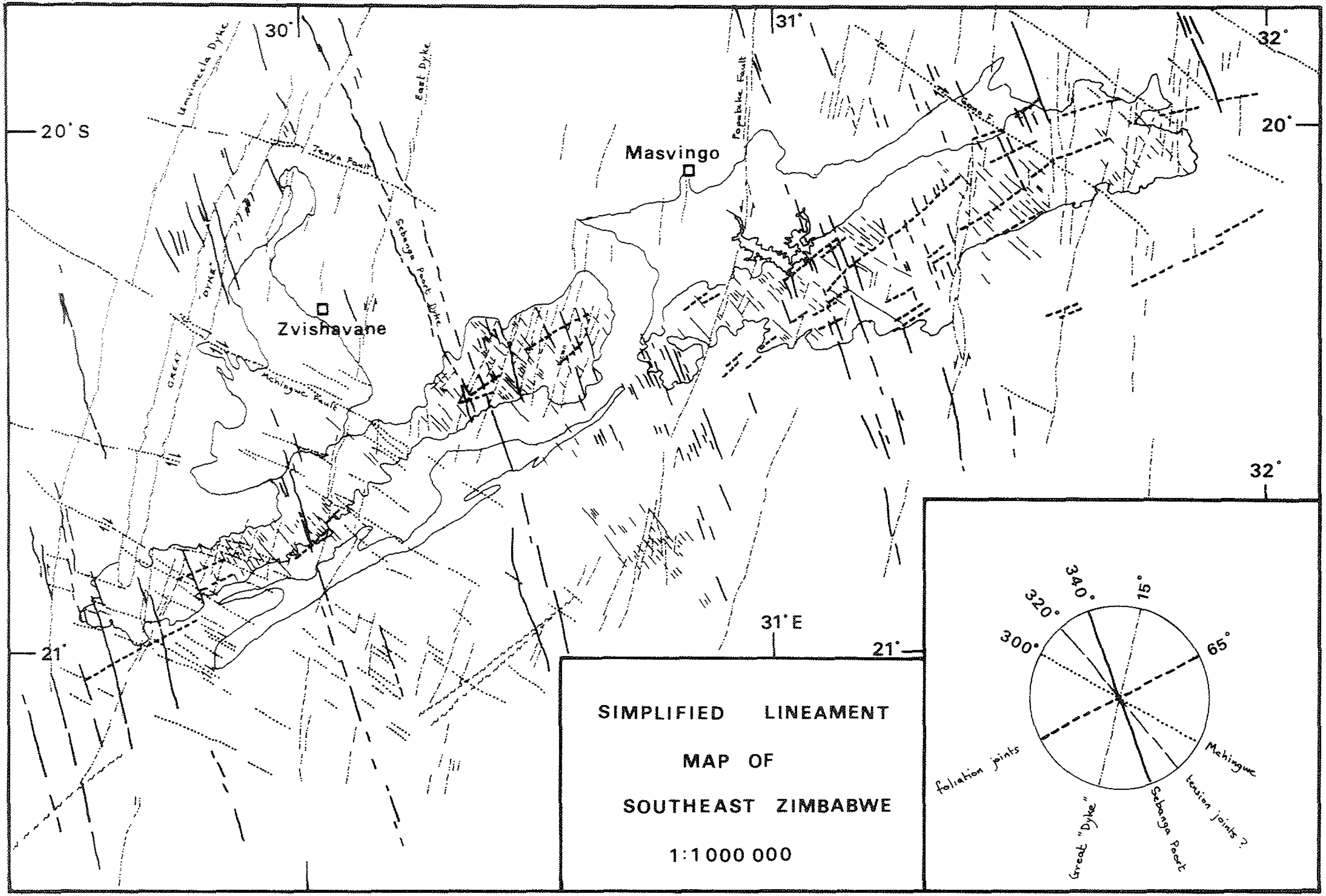


Figure 8: Reduced and simplified lineament map from 1: 250,000 Landsat imagery.

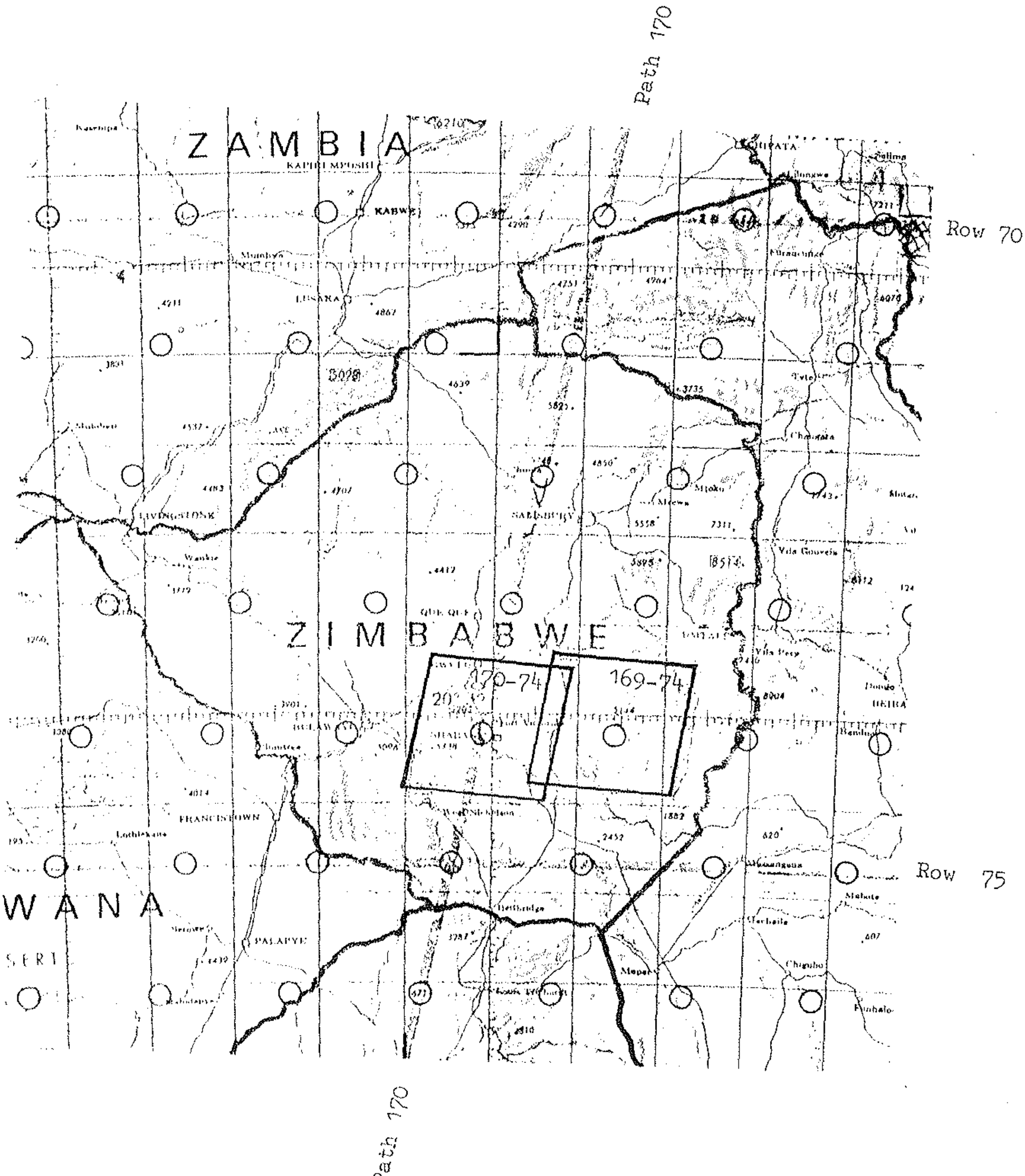


Figure 9: Landsat 4 and 5 World Reference System (WRS) index map of Zimbabwe showing the locations of scenes 169-74 and 170-74.

study.

(i) Emplacement of the Younger Granites: The starting point for describing Late Archaean tectonic events may be conveniently taken as the emplacement of the Younger Granites, in particular, so far as the southern part of the craton is concerned, the batholiths of the Chilimanzi Suite. The Chibi batholith is intruded by the Great "Dyke" and Main Satellites, and clearly predates this important event. The Younger Granites are of particular value for studying brittle deformation events since, because of their high competency, they preserve the best record of fracturing of all rocks of the craton. However, because the imprint of several deformation events is preserved, interpretation of the fracture patterns is complicated and will require detailed field study. Initial fieldwork indicates that the intrusive granites have undergone a complex, multi-stage emplacement and deformation involving both ductile and brittle events as has been documented in granite batholiths elsewhere (e.g. Aucott 1970).

The more or less E to ENE elongation of several of the batholiths (Chibi, Zimbabwe, Razi and possibly Matopos granites) (e.g. Figures 3, 5), appears to be primary feature, perhaps the result of emplacement under a lateral compressive stress or within the confines of a system of faults (Coward 1976). On Landsat imagery a series of long fractures are seen within the Chibi and Zimbabwe batholiths. These are somewhat variable in direction but overall trend sub-parallel to the elongation of the granite bodies. Initial studies of 1:25,000 aerial photographs suggest these to be joints. Fieldwork in the Ndanga-Zaka area to the SE of Lake Kyle has confirmed that here these lineaments correspond to a mineral foliation (weak gneissosity) dipping steeply towards the south, along which has developed a parallel jointing that is in part responsible for the form of individual bornhardts: these kopjes are typically elongate east-west and have a slightly less-steep 'dip' slope on their southern flank and a much steeper northerly flank. It is concluded that the foliation developed as a steep 'flow' layering during the sheet-like emplacement of the batholith from the south, possibly along a direction more or less parallel to the Limpopo Northern Marginal Zone.

At least two other important fracture directions show regional consistency over large portions of the Chibi and Zimbabwe batholiths and are possibly also represented in other Younger Granites, including the Matopos, Shabani and Chinamora batholiths. Further work will be necessary to establish the origin and relative ages of these systems, and for the present interpretations are somewhat speculative.

The first of these directions is orientated NW at approximately 320^{o} (Figure 8). It is developed on Landsat imagery as a fairly intense swarm of short lineaments that generally appear to be cut by all other fracture directions, such that they often appear isolated within fault-bounded blocks. This direction is particularly well developed in the Chibi batholith but is also present intermittently throughout the Zimbabwe batholith. A fracture set having the same general direction and character is seen also in the Matopos and Chinamora batholiths and may be of related origin. The closely spaced development of this set and the lack of observable displacement associated with it, suggest it to be a joint direction. It is tempting to speculate that this represents a tension direction in the granites orientated parallel to the maximum horizontal principal stress at the time of consolidation of the granite. However, the NW direction is not precisely normal to the foliation direction as might perhaps be expected if the maximum stress had been orientated normal to the Limpopo belt and to the overall elongation of the granite belt at the time of granite emplacement. Alternatively, if the principal stress was normal to this trend, then the NW direction might represent a set of incipient dextral shears. Further examination of aerial photograhs, and fieldwork (for example to look for the presence of a mineral lineation within the granite foliation) will be needed to resolve this question.

A second conspicuous fracture set within the Younger Granites trends approximately NNW. This direction is the same as the Sebanga Poort dyke set of post-Great "Dyke" and -East Dyke age, and indeed may be related to this event. Alternatively, it is possible that it developed as an earlier direction at roughly the same time as the NW set: in several examples the NNW direction appears to be developed where the NW direction is lacking and elsewhere there is range of intermediate directions between the two. There is also some evidence to suggest that in the Shabani granite the NNW direction predates the Great "Dyke" (NNE) trend. Here, along both margins of the Great "Dyke", the NNW direction is extremely well developed, although only a few of the fractures seem to actually cut across the "Dyke". (This is possibly more apparent than real). Moreover, it is clear that the NNE-trending fault lying to the east of the Great "Dyke", partly filled by porphyritic dolerite, is later than the NNW direction. However, Martin (1978) notes that the porphyritic dolerite is not magmatically related to the Great "Dyke" and that the fault that it occupies displaces the Jenya Fault which in turn cuts the Great "Dyke". This feature is probably therefore best interpreted as a reactivation (opening) of a Great "Dyke"-trending fracture and intrusion of magma at a later stage.

<u>(ii) Great "Dyke" and satellites</u>: The Great "Dyke", NNE-trending fracture set is extensively developed throughout much of the craton. It may represent a polyphase event involving initial fracturing in the crust, subsequent emplacement of the main lopoliths and satellite intrusions and late reactivation of the fracture set. On Landsat imagery all the important dykes and faults (Umvimeela Dyke, East Dyke, Main Satellites, and Popoteke Fault) are well displayed and, in addition, the intense regional development of this direction is apparent. It is especially conspicuous within the Chibi batholith where it shows apparent sinistral displacement of the granite margins and crosscuts the

early 320^{o} jointing. A sinistral sense of movement is also evident where the Popoteke Fault cuts the Masvingo greenstone belt as mapped by Wilson (1964). Initial fieldwork in the Chibi area indicates, however, that fractures of this trend show small dextral displacements; it is possible that such movements represent later reactivation under a different stress regime. Important developments of the NNE trend are also present across much of the Zimababwe batholith. One such large lineament is interpreted as an important, previously unidentified, shear zone passing through the Ndanga-Zaka area and extending SSW to the east of Bangala Dam.

Wilson et al. (in press; Wilson in prep.) envisaged the tectonic events leading to emplacement of the Great "Dyke" as first the craton-wide development of NNE sinistral strike-slip faults under a NNW directed horizontal maximum principal stress (accompanying the thrusting of the Northern Marginal Zone granulites onto the craton) and second the opening of this direction during a period of extension with attendant dyke emplacement. If, indeed, a set of sinistral strike-slip shears did develop as a late stage response to the same stresses that led to the emplacement of the Younger Granites, it would imply a maximum principal stress just about normal to the elongation of the granite batholiths. This might in turn imply that the NW fractures are dextral shears, as suggested earlier.

Whatever the initial origin of the NNE fractures, there can be little doubt that a tensional regime existed at the time of emplacement of the magmas of the layered complexes. The tensional opening of the fractures might have resulted from updoming of the crust, perhaps associated with the rise of magma. It seems improbable that the Great "Dyke" occupies a large 'tension gash': rather the structure could have formed in a manner analagous to caldera collapse. Magma, perhaps having been extruded at the surface into a shallow graben-like depression, or intruded as an extensive sill above a linear arching of the craton, collapsed back upon itself along a series of steep normal fractures parallel to the margins. This model is similar to that originally proposed by Worst (1958). During the cooling and consolidation of the "Dyke", contraction appears to have led to the development of numerous normal faults lying transverse to the local trend of the intrusion. It is possible that further longitudinal faulting would have accompanied such shrinkage so as to further accentuate the down-faulted margins of the body.

(iii) WNW dextral strike-slip faulting: The next major brittle deformation event to affect the craton appears to have been fracturing along a series of extensive WNW dextral strike-slip shears, including the Mchingwe, Nuanetsi, Jenya faults and possibly also the Gono Fault. Where the Mchingwe Fault cuts the Great "Dyke" a 3.5 km dextral offset is seen, although Worst (1958) notes that this fault also shows a normal downthrow of about 500 m. Interestingly, where this fault penetrates the Belingwe greenstone belt, the nature of the deformation can be seen to gradually change in response to the lesser competence of these rocks, from brittle failure to semi-ductile folding. In the case of the Jenya Fault, it is considered that only the western segment cutting the Great "Dyke", was active at this time: the eastern section of this fault through the Mushandike granite is regarded as having remained essentially inactive after its much earlier sinistral movement (possibly associated with the Mashaba-Chibi dyke/fracture set). On Landsat imagery this WNW set of lineaments is particularly well developed to the east and southeast of the southern termination of the Great "Dyke" across the Chibi granite, the greenstones and the Northern Marginal Zone granulites. Wherever evidence is seen on the imagery, the sense of movement is dextral. This would again imply a NNW horizontal maximum principal stress. Wilson et al. (in press) suggested that this fracture direction originated earlier as a conjugate set with the Great "Dyke" set, and was presumably later reactivated. The age of this faulting direction is, however, in some doubt. Where the Mchingwe Fault cuts the Great "Dyke" a parallel fault is filled by a major dolerite dyke which Wilson (op. cit.) reports as having a palaeomagnetic pole position of Mashonaland Igneous Event character: this would date it at around 1830 Ma. It should also be noted that Stowe (1979; 1980) suggested that the Jenya Fault was in fact later than the Sebanga Poort dyke. Clearly the evidence is equivocal and it may be the two directions (i.e. WNW and NNW) are of similar age.

(iv) Sebanga Poort fractures & dykes: Several long fractures and dykes trend NNW across the southern part of the craton and Northern Marginal Zone of the Limpopo Belt. The principal intrusive, the Sebanga Poort Dyke, extends discontinuously for approximately 300 km. This and other NNW dykes, including the Bubi and Crystal Springs swarms which occur to the south of the Great "Dyke", were grouped by Wilson et al. (in press) as part of the Mashonaland Igneous Event. NNW lineaments, some representing dykes, appear to be more abundant on satellite imagery than mapped, although as noted earlier some of these may correspond to an earlier fracture direction of pre-Great "Dyke" age. In detail, the Sebanga Poort and other dykes in this set are extremely irregular in width and direction, and are seen to bifurcate. Apart from the Bubi and Crystal Springs dykes, which Robertson & van Breemen (1970) descibe as infilling shears, the NNW fractures appear to be tension fractures (Wilson et al. in press). It is possible, however, that dykes were emplaced along opened-up, pre-existing fractures during a period of ENE-WSW tension.

(v) Late ENE dextral faults & dykes: In the area to the east of Mashaba a series of ENE-trending dykes and faults dextrally displace the East Dyke and possibly also dykes of the Sebanga Poort set. These dykes trend parallel to some of the older dykes of the Mashaba-Chibi swarm and are indicated on Wilson's (1968) geological map to be amphibolitised. Whether or not this represents a separate dyke emplacement event, or merely reactivation along older dykes, it is clear that at least in this area a significant late strike-slip faulting event occurred implying a maximum principal stress orientated WNW.

(vi) Discussion: Several models are capable of explaining the pattern of fracturing seen in southern Zimbabwe, and without more information relating to fracture plane movements, it is not possible to favour one of these to the exclusion of the others. One possible scheme of events is illustrated in Figure 10 and described below.

(1) Emplacement of the Chilimanzi Suite of Younger Granites along a zone of crustal weakness roughly parallel to the Limpopo Belt (i.e. approximately 065°) during a period of roughly NW - SE regional compression (140°-320°). Development of a sinuous flow foliation in the granites parallel to the confining margins of the pluton during ductile emplacement, and of incipient tension fractures (joints) parallel to the maximum principal stress during final cooling. Formation of parallel NW joints also in some of the Northern Marginal Zone granulites as a result of deformation under the same stresses.

(2) Rotation of the horizontal maximum principal stress vector to give roughly NNW-SSE compression. Development of NNE fractures with minor sinistral strike-slip motion along some (e.g. Popoteke). Possible dextral strike-slip reactivation of the earlier granite NW tension joints.

(3) Emplacement of the Great "Dyke" magmas along pre-existing NNE shears opened up under a phase of regional WNW-ESE tension, possibly associated with axial up-warping and graben subsidence. Penecontemporaneous

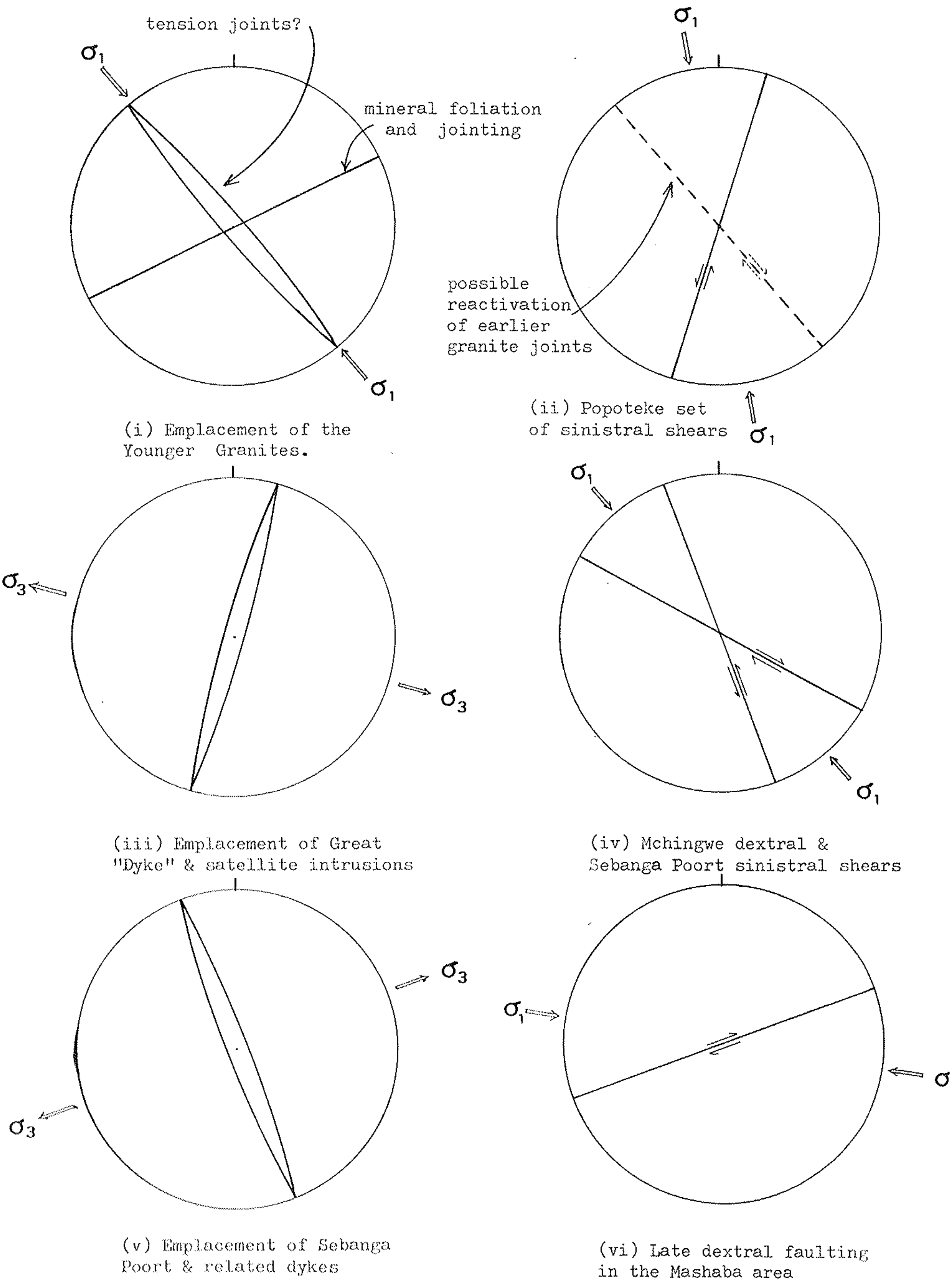


Figure 10: Late Archaean-Proterozoic stress regimes in the Zimbabwe craton

intrusion of the Umvimeela Dyke, East Dyke and Main Satellites.

(4) Regional development of WNW dextral strike-slip faults (incl.the Mchingwe, Nuanetsi, Jenya and Gono faults) during a period of renewed horizontal compression along a 145^{o}-325^{o} axis. It is possible that the Sebanga Poort fractures were also initiated at approximately this time as sinistral strike-slip (conjugate ?) shears, perhaps as a result of a slight anticlockwise rotation of the principal compressive stress vector. Late dyke infilling of some shears during tensional re-opening under a roughly NNE-SSE directed tension.

(5) Intrusion of the Sebanga Poort and related dykes along NNW trending fractures during a period of roughly ENE-WSW regional tension. The NNW fractures were either initiated at this time or were opened-up, pre-existing (possibly shear) fractures.

(6) In the Mashaba area, a series of "metadolerite" dykes trending roughly ENE cut the East Dyke and show dextral strike-slip displacement resulting from WNW-ESE directed compression. The dykes possibly represent earlier Mashaba-Chibi dykes sheared during this later deformation or, more probably, a later set of intrusions emplaced into the shears during subsequent NNW-SSE tension.

(7) Dykes of presumed late Karroo age occupy two trends (WNW and ENE) in the south of the country and are very evident in places on imagery and photography. It has been suggested that, together with the Lebombo swarm in South Africa, they form a triple junction related to the break-up of Gondwanaland (Reeves 1978;

Wilson *et al.* in press). In SE Zimbabwe the main dyke direction is ENE suggesting emplacement under NNW-SSE tension.

6. TECTONIC MODELS IN GROUNDWATER EXPLORATION

Rock stress and fracturing were discussed in some detail by Greenbaum (1985). The principal concepts are summarised here.

Stress in the earth may be described in terms of three mutually perpendicular components denoted the maximum (σ_1), intermediate (σ_2) and minimum (σ_3) principal stresses. At high stress values deformation results in brittle fracturing. Under conditions of pure shear failure occurs by shearing along conjugate planes orientated at about 30^o, on average, to the maximum principal stress axis; the intersection of these two planes contains the intermediate stress axis. Irregular tension fractures may form in the $\sigma_1 - \sigma_2$ plane as an early response to compressional stress but tend to give way to shearing as the deformation continues. Anderson (1951) explained the occurrence of normal, reverse and strike-slip (wrench) faults as due to differences in the orientation of the three principal stress vectors (Figure 11).

Where the existence of conjugate shears can be demonstrated, their orientations can be used to deduce the directions of the palaeostress vectors. In practice, however, it is often difficult to prove that a conjugate relationship in fact exists between two shear directions, which could equally have formed at different times under different stress conditions (Figure 12). Moreover, rocks may also deform in an essentially semi-ductile manner by simple shear, giving rise to a variety of other fracture directions (Tchalenko & Ambraseys 1970; Wilcox *et al.* 1973; Hancock 1985) (Figure 13). It is thus apparent that

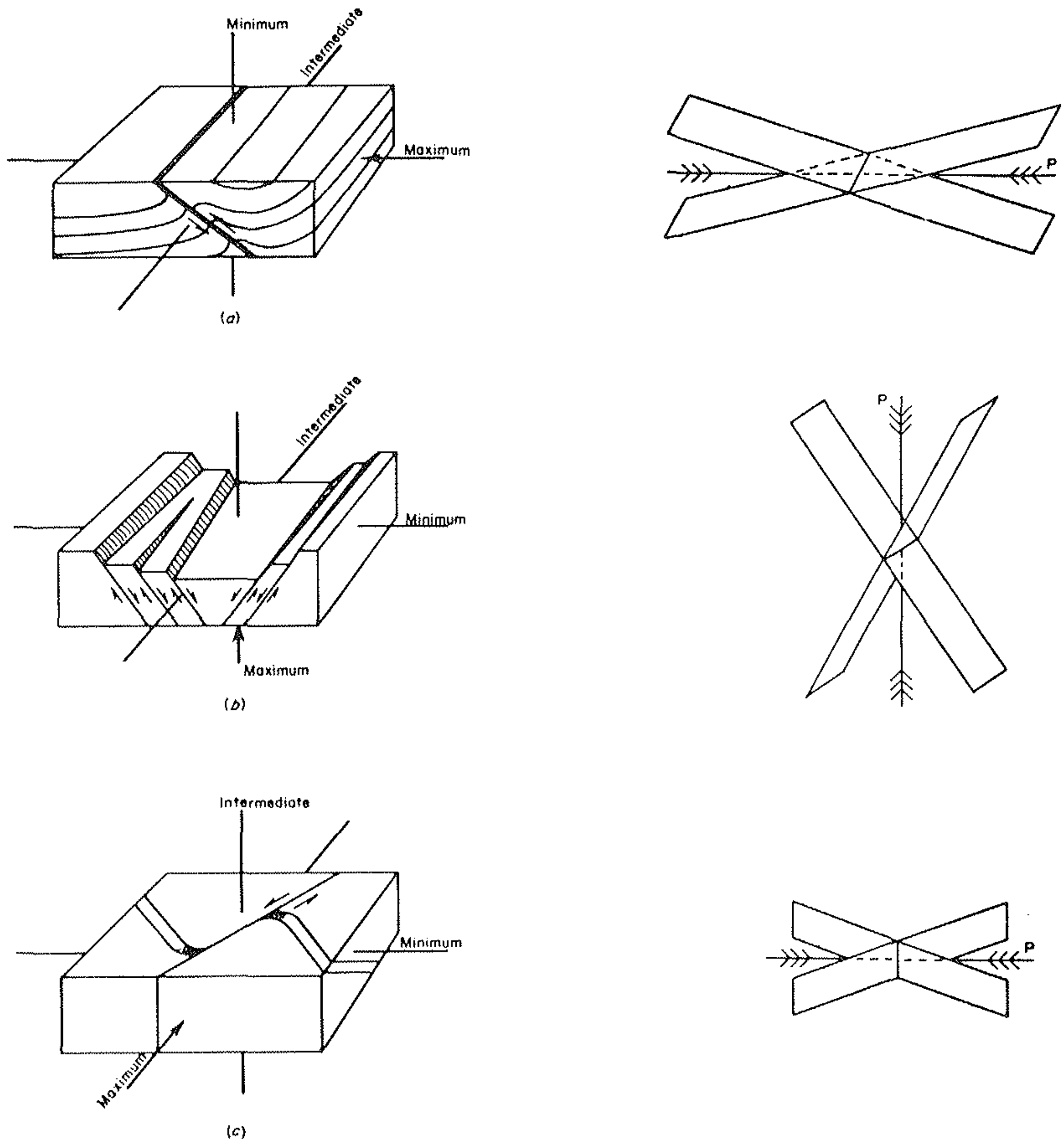
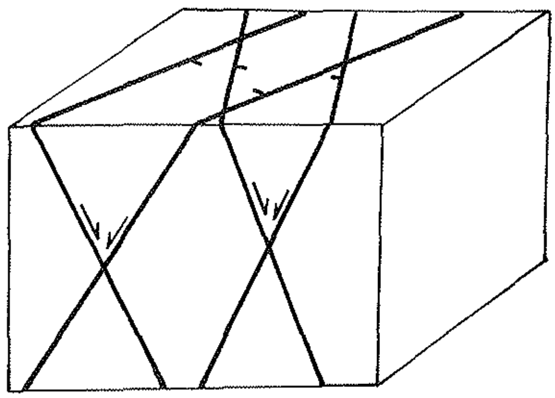
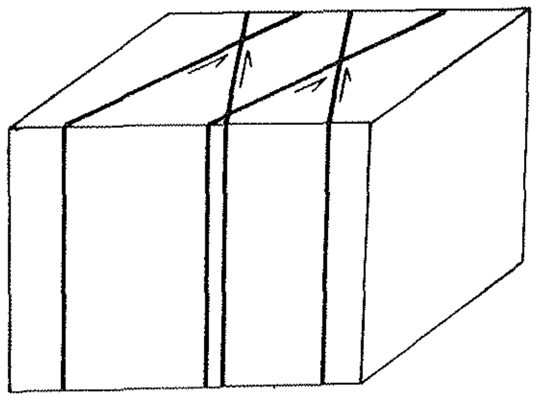


Figure 11: Relationship between principal stresses and common fault orientations for thrust, normal and strike-slip faults. (After Anderson 1951).



(a)



(b)

Figure 12: Alternative explanations of intersecting sets of surface lineaments. (a) 2 sets of normal faults formed under different stress configurations (b) conjugate strike-slip faults.

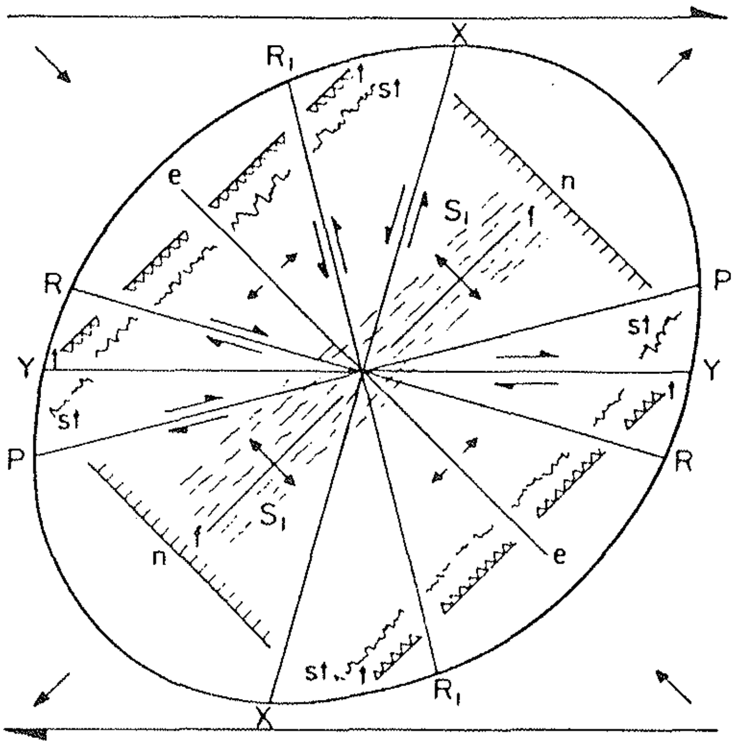


Figure 13: Diagram illustrating en echelon structures characteristic of strike-slip fault zones produced by simple shear. R and R_1 Riedel and conjugate Riedel shears; P, X, Y and P-, X- and Y-shears; e extension joint, fissure or vein; n normal fault; t thrust; st stylolite; f fold; S_1 cleavage or other foliation. (From Hancock 1985).

conclusions regarding palaeostress directions are subject to considerable uncertainties, especially where fractures have been interpreted by remote sensing methods and where ground control data is lacking. In older rocks that have undergone several deformations the situation is even more complicated: not only is there the problem of identifying conjugate shear sets, but also the possibility that older fracture planes will have been reactivated under conditions that deviate from normal stress/shear relationships.

These considerations are of particular importance in the context of hydrogeology where the nature of a fracture (i.e. shear or tension) is often regarded as relevant to its water-bearing potential. In Botswana, for example, considerable debate surrounds the theoretical validity and practical usefulness of a model proposed by VIAK AB (a Swedish firm of hydrogeological consultants) which purports to identify shear and tension fractures from the regional pattern of lineaments (Greenbaum 1985). Because of the importance that such models can assume in exploration, and in view of the considerable reservations that must apply, this topic is reviewed in detail below.

The VIAK model is illustrated in Figure 14; it assumes that an observed regional pattern of rhomb-shaped lineament intersections is the consequence of two episodes of wrench faulting resulting from a 90^{o} rotation of the maximum and minimum horizontal principal stress axes. It also assumes that, in addition to conjugate shears formed during each phase of shearing, tension gashes parallel to σ_1 and σ_2 were formed: VIAK regard these as having the best potential for the occurrence of groundwater. Presumably these tension fractures would be identified on imagery/photographs as subtle lineaments and would form the focus for further exploration. VIAK's model has been adopted in more recent studies by BRGM (1985a, 1985b, 1985c).

Although drilling for water in Botswana, partly guided by the

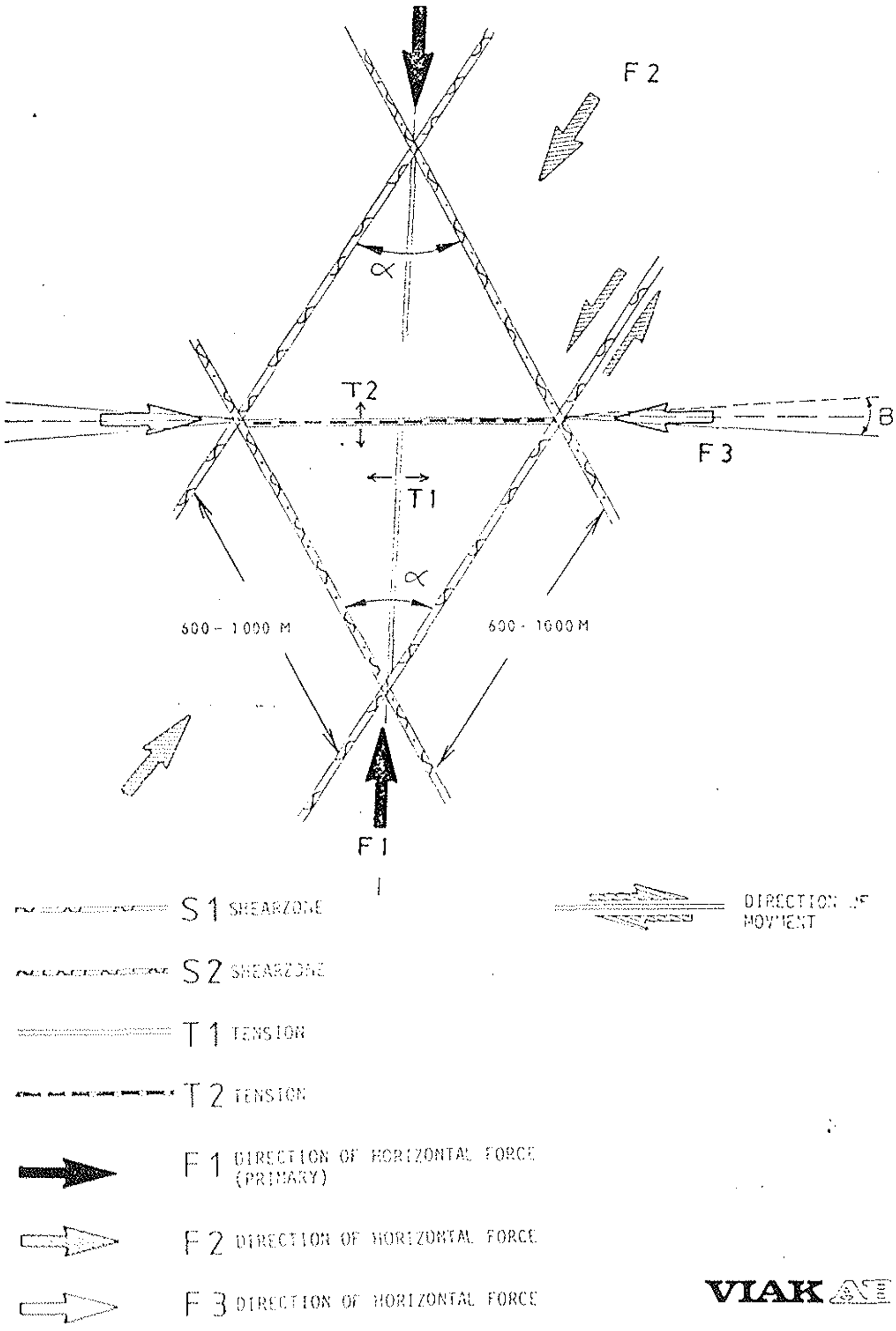


Figure 14: The VIAK AB simplified tectonic model for fracturing of brittle rocks.

VIAK approach, has had a good record of success, there are several fundamental reasons to doubt the validity of the VIAK model and its more general applicability, for example in Zimbabwe.

(1) Evidence of several phases of strike-slip and normal faulting in Zimbabwe indicate that here any simplistic model involving two main episodes of deformation is untenable. It seems likely that Botswana will have experienced a similar tectonic history. This is somewhat confirmed by a rather 'astonishing' aerial photograph lineament interpretation contained in a recent BRGM hydrogeological study (1985c), which depicts the presence of literally thousands of straight lineaments of all orientations covering their study area! Whereas such interpretations are scientifically meaningless, it does perhaps indicate that the fracture pattern in Botswana is far from simple.

(2) Even if a rhomb pattern of lineaments is found to exist, it is theoretically unlikely to be the result of two episodes of strike-slip faulting orientated at 90°, since the second maximum principal stress would make an unacceptable angle of 60° with each of the two original conjugate shears. Such a rhomb pattern could simply be the result of either (a) a single phase of strike-slip faulting or (b) two unrelated periods of normal faulting (refer to Figure 12). In practice, the multiphase nature of the fracturing means that an infinity of rhombs could be defined.

(3) As shown in Figure 13, even if horizontal compression is assumed, there are many other types of fracture that can develop besides conjugate shears. Remote sensing data alone is unlikely to be able to

distinguish between these. In examples seen from Botswana, angles between so-called conjugate shears as low as 30° have been noted. This casts considerable doubt on the true nature of these fractures.

In addition to these criticisms specific to the VIAK model, other more general problems apply to tectonic models in hydrogeology.

(4) Even if it is possible to distinguish between what were originally shear and tension fractures, it is unlikely that during reorientation of the stress field, and re-activation of older movement planes (as in the VIAK model), the original character of a fracture would be preserved. Thus, tension cracks would have developed into shears and shears would have suffered repeated movements or have been opened under tension.

(5) By their nature tension fractures tend to be less regular and less continuous than shear fractures. Thus, despite their possibly more open nature, they may lack the continuity and inter-connections with other fractures necessary to provide good transmissivity.

(6) Conversely, despite the theoretically closed nature of shear fractures, their comparatively greater length and probable continuity, could mean that their transmissivity is higher than that of tension fractures.

(7) Fault movement along a shear fracture is likely to have produced a zone of crushing that will be liable to increased weathering with concomitant increase in the hydraulic storage capacity and transmissivity. Any such increase may, however, may be nullified by clogging of the fracture with clay formed during such weathering.

(8) Discussions with hydrogeologists in Botswana confirm that at depths of 100 m to 250 m, most fractures in crystalline basement are closed, probably as a result of increased lithostatic pressure. Field evidence indicates that, in a similar way, fractures of all origins open up (e.g. shear and tension fractures; weakness planes parallel to mineral foliation), and new ones form (e.g. sheet exfoliation on granite bornhardts), in the near-surface zone as a result of unloading. If this is so, then the distinction between original shear and tension fractures becomes less important.

(9) Finally, it seems inherently unwise to exclude as drilling targets fractures of significant size merely on the basis of a very hypothetical, theoetically unjustified and practically unproven model. I was informed in Botswana (P. Larkin pers. comm. 1985) that the detailed VIAK model has a firmer theoretical base than the summary version published. However, as few further details were available it is difficult to comment on this.

7. DISCUSSION AND FURTHER WORK

The work reported on here represents the preliminary findings of a study that is continuing. A literature review has provided the necessary background for a detailed remote sensing lineament analysis using Landsat imagery and aerial photograhs. So far, a generalised interpretation of 1:250,000 false colour composites of two scenes has been carried out as well as an interpretation of 1:80,000 aerial photographs for about two-thirds of the

Masvingo Province and of 1:25,000 photographs for several sub-areas in which reconnaissance fieldwork during 1985 was carried out. Much of this data remains to be analysed in detail. In addition, computer tapes of two Landsat MSS scenes (169-74 and 170-74) have been obtained and will, in the coming year, be enhanced on the Keyworth I^2S image analysis system over specific areas of interest. Once sub-areas for detailed study have been decided upon, further interpretation of the relevant 1:25,000 aerial photographs will be carried out in conjunction with additional fieldwork.

Several problems remain in relation to interpreting the relative ages, senses of movement and present-day nature of fractures interpreted from remote sensing data. The planned fieldwork will attempt to resolve these uncertainties, although it is not expected that field evidence will unambiguously answer all of the questions. Other parts of the project will examine possible correlations between borehole yield, geology and structure. Thus in conjunction with surface and borehole geophysics, it may be possible to begin to understand the importance of rock fracturing to water yield in this area. Nevertheless, problems in this approach can be anticipated, notably that (i) most boreholes will not have been sited on a lineament and the relevance of a site merely 'near to', rather than 'on', a fracture is uncertain, and (ii) most boreholes will not have penetrated the bedrock to any significant extent. In view of this it may be necessary to consider drilling some additional research holes into bedrock.

At a practical level some thought needs to be given to ways in which any positive results from this research can be applied in Zimbabwe given the typical string development of most communities and the consequent need to site wells close to such habitation. With these constraints, the development of high-yielding boreholes at greater distances from existing dwellings might be seen as unacceptable. Regardless of this, however, it is clear from reconnaissance fieldwork that, in general, poor use is made of photogeological techniques in siting boreholes, many of which appear to be simply located down a convenient path and within 10 to 20 metres of a valley bottom/stream bed. Even given the socialogical/logistical constraints referred to above, and the difficulties of recognising lineaments where outcrop is limited or absent, siting could benefit from the use of sub-regional and 'local-area' lineament analysis. Using this approach, subtle lineaments could be more reliably interpreted by comparison with the local pattern, or possible extensions of prominent lineaments from surrounding regions inferred. Targets could then be tested using normal geophysical methods.

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