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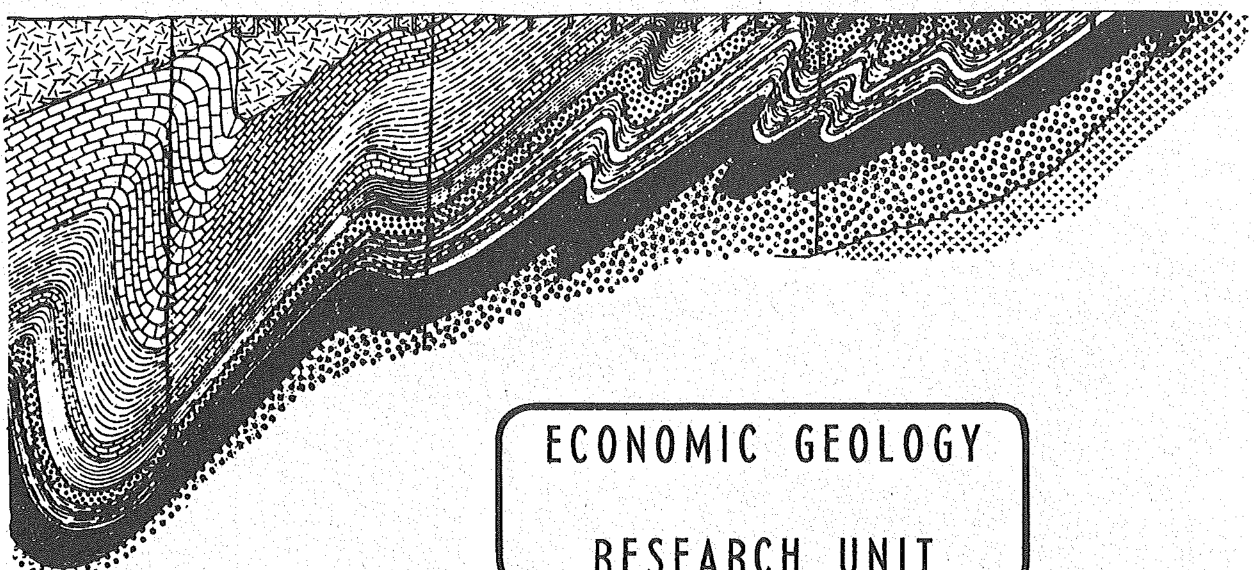

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 49

A REAPPRAISAL OF SOME ASPECTS OF PRECAMBRIAN SHIELD GEOLOGY

C.R. ANHAEUSSER, R. MASON, M.J. VILJOEN
R.P. VILJOEN

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by

C. R. ANHAEUSSER
Research Fellow, Economic Geology Research Unit

R. MASON
Visiting Research Fellow from the
Geological Survey of Botswana

M. J. VILJOEN and R. P. VILJOEN
C.S.I.R. Research Officers, Upper Mantle Project

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September, 1968

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ABSTRACT

Attention is drawn to some of the misconceptions regarding the ancient crystalline shields, and an attempt is made to clarify some of the ideas held on their geology. In Southern Africa, the Precambrian shield is well-represented and exposed, and recent studies of it reveal a clear and well-defined pattern of events in its evolution.

The very ancient, stable, cratonic nucleii incorporating the greenstone belts are termed "The Earliest Precambrian". Traversing the shield areas and surrounding the cratonic nucleii are large, elongated, highly metamorphosed and granitized "Precambrian Mobile Belts". Although younger than, and totally different in character to, the cratons which they tend to encircle, they nevertheless form an integral part of the crystalline shields.

The fundamental elements of the geology of the greenstone belts within the cratonic nucleii, together with a distinctive pattern of relationships between the greenstone belts and their surrounding granitic terrain are repeated with remarkable consistency in other shield areas of the world, especially in Canada and Western Australia. The geological features which typify and contribute to the establishment of this highly distinctive pattern are outlined in the text and demonstrated with the aid of tables and diagrams. The world-wide uniformity of the stratigraphy, structure, metamorphism, mineralization, associated granites, and geotectonic setting of the greenstone belts is stressed.

An attempt is made to reconstruct an evolutionary model of the development of the early Precambrian granite-greenstone belt terrain. This avoids direct comparisons with younger geological features and events, particularly the younger, Alpine-type orogenic belts with which early Precambrian geology has frequently been compared and equated. The mobile belts are briefly discussed and again it is suggested that their evolution was not necessarily along the lines suggested for Alpine orogenesis.

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A REAPPRAISAL OF SOME ASPECTS OF PRECAMBRIAN SHIELD GEOLOGY

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NOMENCLATURE

In the text, reference has been made to "shield", "craton", "greenstone belt" and "mobile belt". Since no consistent usage has yet been applied to these terms it was considered necessary to define them in terms of the usage accorded them in this paper. These definitions are open to criticism and probably require further modification.

"Shield" is used to describe a continental or sub-continental area of crystalline rocks of Precambrian age.

"Craton" is used to describe stable nucleii within shield areas which consist of complex granitic terrains incorporating early Precambrian "greenstone belts". They form composite and well-defined entities which have been unaffected by any major tectono-thermal event for the last 2,400 m. yrs.

"Greenstone belt" is used to describe the distinctive meta-volcanic and sedimentary assemblages which occur as scattered remnants on the cratons, forming an essential part of the latter. "Greenstones" (meta-basalts and andesites) generally predominate in these belts and important features are the low-grade of metamorphism over the major parts of the belts, and tight folding.

"Mobile belt" is used to describe the younger, linear, metamorphic belts which tend to surround the ancient cratonic nucleii of shield areas and which are characterized by high-grade metamorphism, granitization and often by transcurrent dislocation. These belts may be complex and may incorporate several recognizable tectono-thermal events in a single belt (e.g. the Mozambique), but nevertheless remain as entities in the shield areas. The term "mobile belt" is used here to replace "orogenic belt", which is considered to imply a geotectonic evolution involving geosynclines and orogeny — something that has never been satisfactorily established.

INTRODUCTION

> "There was a time when the Alps were considered, especially by European geologists, a model for all mountain chains"
>
> Trümpy (1960)

Alpine geology has influenced thinking on the Precambrian for many years, and the concepts of geosynclines, orogeny, and all that these imply, in terms of mountain-building, deep burial, regional metamorphism, granitization, and igneous intrusion, have been applied to the Precambrian in an effort to understand Precambrian evolution. The results have not only been unconvincing, but they have also led to confusion in the many cases in which the facts of Precambrian geology have not fitted theories based essentially on Alpine geology. The use of "geosyncline" in Precambrian geology is considered to be misleading in most cases, especially when applied to mobile belts (the "orogenic belts" of Holmes, 1951), and also in respect of the early Precambrian "greenstone" belts. One of the major hindrances which has prevented understanding of the Precambrian shield areas has been the concept of "the roots of mountain chains", linked inherently to the concept of regional metamorphism controlled in its intensity by depth of burial. Read (1902) argued strongly for a concept of regional metamorphism controlled by "geological depth", not depth of burial within the crust, and it is becoming more and more established that regional metamorphism is only related to crustal depth in that its environment has been exposed to high heat flow and tectonic stresses related to sub-crustal agencies. The mobile belts represent disturbed linear zones in the earth's crust, and are frequently related to large transcurrent faults. Mantle disturbances along these zones must have been considerable, and it is possible that high heat flow in these zones was related to upwelling of mantle material underneath them. There is no necessity to invoke deep burial to explain the metamorphic and structural features of the mobile belts.

The early Precambrian greenstone belts have been variously regarded as individual orogenic belts (Brock, 1959), or as remnants of once extensive orogenic belts which covered the shield areas (Holmes, 1965). However, it is suggested that these greenstone belts were not orogenic belts at all, and that they formed as discrete depositories where their evolution was controlled by a pre-existing structural pattern, the nature of the early crust, and the granites which surround and intrude them. They are completely different in nature and origin from the metamorphic mobile belts which surround the early Precambrian cratons. The world-wide uniformity of early Precambrian greenstone belts is remarkable, and it is suggested that their correlation should be based on a combination of factors, such as lithology, structure, metamorphism, relationship to surrounding granites, and the overall geotectonic setting. The greenstone belts are peculiar entities, and, when regarded as such, there seems to be little justification for the proliferation of stratigraphic nomenclature which has arisen in certain shield areas, and for the division of greenstones and metasedimentary rocks into separate systems. The lithological associations of the greenstone belts are well-established, and, apart from the institution of local formational names there is no necessity to complicate the issue of correlation. Obviously, in such belts, there will be minor differences of sequence and facies changes, together with local unconformities, but, essentially, these belts are so similar in their properties and associations that local variations are unimportant.

Some of the major Precambrian structures in Africa were first recognised by Krenkel (1928), and his "Geologie Afrikas" represents a notable landmark in the elucidation of the Precambrian in Africa. Twenty years later, Holmes (1951) presented a paper on "The sequence of Precambrian orogenic belts in South and Central Africa", in which radiometric age determination was introduced as a method of differentiating the Precambrian rocks into various groupings. The pioneer work by Holmes led to a spate of determinations in the following years, and these have shed much light on the relative ages of tectono-thermal events in Africa and elsewhere. Three major papers which summarize the results of radiometric dating in Africa south of the equator are those by Holmes and Cahen (1955), Nicolaysen (1962), and Cahen and Snelling (1966). Systematic geological mapping, which has been carried out by the various African geological surveys, has provided a sound basis for the establishment of the early Precambrian pattern and sequence of geological events. Part of the African shield is represented in Figure 1 which shows the relationship of the early Precambrian cratonic nucleii to the mobile belts.

Mention should be made here of the great contribution from photogeological interpretation towards the mapping of Precambrian terrain in Africa. Photogeological interpretation provides a method of covering large areas very rapidly, and allows the geologist to view his problems on a regional scale — important factors in elucidating African geology. Hepworth (1967) has recently drawn attention to the use of photogeology in the recognition and elucidation of ancient mobile belts.

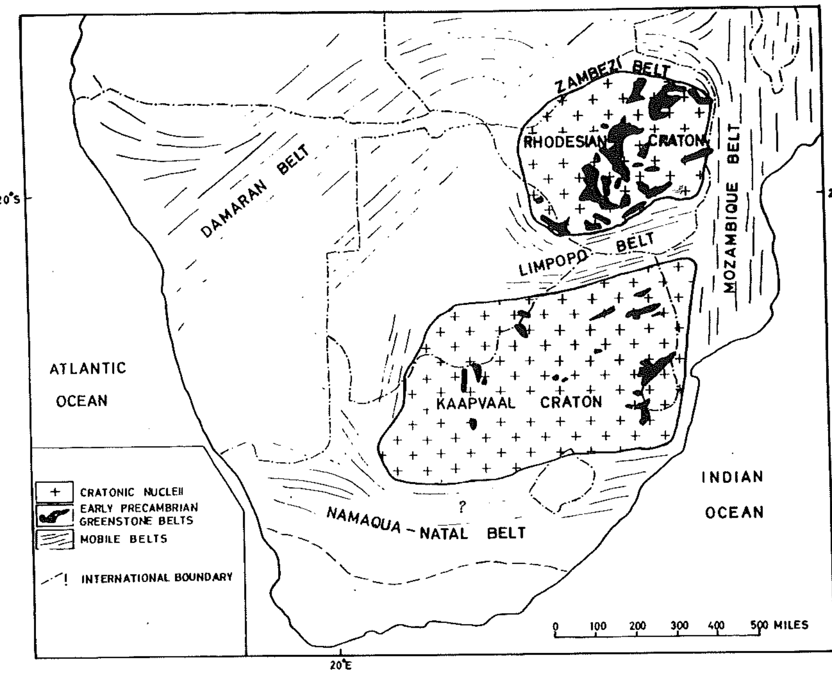

Figure 1 : The Southern African crystalline shield stripped of its younger cover showing the ancient greenstone-granite cratons and the encircling, younger, mobile metamorphic belts.

It is the purpose of this contribution to try to clarify the nature and evolution of early Precambrian greenstone belts and the geotectonic setting in which they occur, and to assess the nature, evolution, and significance of the mobile belts which form such major structures across shield areas.

THE EARLIEST PRECAMBRIAN

A. THE EARLIEST PRECAMBRIAN CRUST

The early Precambrian cratons in their present form invariably constitute the oldest and most stable part of the continents. These ancient cratonic nucleii of the shields have ages ranging from about 2,400 to 3,400 million years, and are composed predominantly of a complex granitic terrain in which the strongly folded greenstone belts appear to "float" in the form of synclinorial "keels" or "rafts" (see Figure 2).

The granitic assemblage of the shields, as will be discussed later, is probably largely of a secondary origin, having been derived from the mantle and from reworked primitive crust. The addition of younger granitic material has resulted in appreciable thickening and, presumably, reconstitution or obliteration of an earlier, probably more primitive crust. It thus seems unlikely that unaltered remains of early crustal material will be found although it is possible that parts of the migmatite of the shields might represent altered and granitized vestiges of an early crust. This is open to considerable doubt, however, so that whatever is surmized about the nature of the primitive crust must be on theoretical grounds, with important limitations being imposed by the association of rock-types found in the greenstone belts.

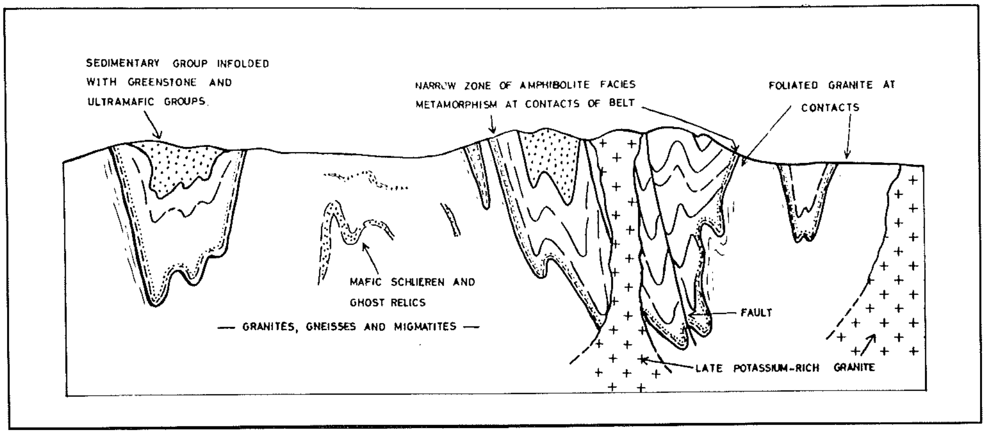

Figure 2 : Schematic cross-section through portion of a granite-greenstone craton.

Certain features of the greenstone belts suggest an origin on a relatively thin crust. In particular their rather close similarity to the recently evolved island arcs of the circum-Pacific points to a somewhat analogous mode and environment of formation. Crustal thicknesses in this type of environment appear to be about 12 to 15 km. Other features, suggesting emplacement on a much thinner crust than at present, are the telescoped nature of the metamorphic aureoles at contacts with the younger granites, and the bimodal nature of the mineral facies (Engel, 1966). It has been pointed out (A.E.J. Engel, in Roering, 1967) that the non-development of a blueschist facies of metamorphism in greenstone belts also favours a thin early crust and a steep thermal gradient in early Precambrian times. Another line of evidence stems from the chemistry of the metabasalts. They are generally low-potassium tholeiites, with compositions approximating closely those of oceanic tholeiites. The primitive (uncontaminated) nature of these metabasalts is possibly to be ascribed to their having passed through a relatively thin sialic and/or basaltic crust in very early Pre-cambrian times (Engel et al, 1965). It should be stressed, however, that subsequent events may have brought about interchange of elements, and that the low-potassium values of these metabasalts do not prove their original nature conclusively.

With available evidence thus pointing to an early, thin, unstable, primitive crust, the question now remains as to what the nature of this crust was, and how it developed to become the thickest and most stable part of the continents in subsequent times. The thickening appears to be almost entirely related to the development and emplacement of the vast "sea" of granite mentioned above, and will be discussed in a later section. Of concern here is the nature and mode of formation of the primordial crust.

Certain authors, notably Gill (1961), Wilson (1959), and Lawson (1932), regard the first-formed crust as having been of mafic composition. This crust developed, most probably, by the outflow of basaltic lava. The sial is envisaged as having developed by later invasion of granitic and granodioritic material from below certain areas of the primeval crust. Assisted by geological processes, these later rose as sialic continental blocks. Many other workers, namely Vening Meinesz (1950), Poldevaart (1955), and Ramberg (1964), assume a primeval scum, or crust, of sialic composition. The present non-uniform later distribution of the sialic crust is thought to be the result of reworking during orogenesis, and to the "pulling" of the original sial away from the oceanic areas. This resulted in a consequent thickening of sial in the continental area. Ramberg (1964) formulated a model whereby the original, thin, sialic, crust was forced apart by the emplacement and subsequent sinking of heavy mafic magma. The sialic material is envisaged as having been forced, at first laterally, and then vertically, to form the primitive continental nucleii, while the heavy mafic material sank to form the ocean basins.

There is evidence in Southern Africa, at least, that the greenstone belts were formed on a sialic crust, however thin it might have been, with the development of early sediments which must have been derived from a granitic source.

Thus, whatever was the mode of formation, and later concentration of sialic material to form the primitive continental nucleii, it is generally agreed that this material was of a sialic nature. There is a possibility, however, that it was more mafic than present sial (Ramberg, 1964).

Many of the features of greenstone belts, and particularly the rather rapid thinning of the stratigraphy away from a thick pile along a central axis, clearly suggests deposition in elongate troughs or down-buckles in the earth's crust. The mode of formation, cause of localization, and pronounced orientation of the greenstone depositories are open to much speculation, because of the difficulty of deciphering and interpreting the earliest processes in the earth's crust. The authors visualize two possible processes. Following a more uniformitarian view, each of the greenstone belts may be envisaged as having developed in downwarps at the interface between a thin, primitive, sialic crust and a primitive oceanic-type crust (see Figure 3). As noted previously, the greenstone assemblages have marked similarities with the more recent island arcs which have developed in a similar position.

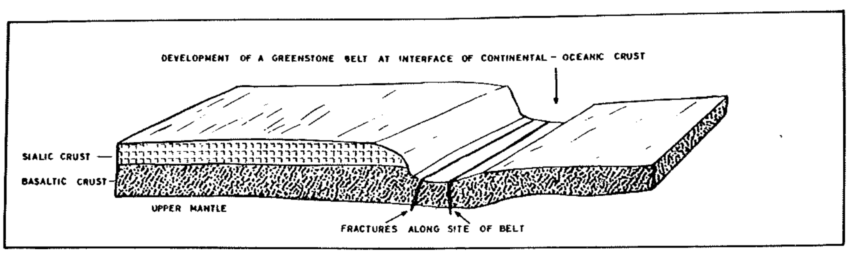

Figure 3 : Possible development of a greenstone depository following a more uniformitarian view.

The modern island arcs, however, are formed at the interface of a thicker, more highly evolved, recent, continental crust, and a correspondingly thicker oceanic crust. Following this idea, and the concept of continental accretion, as suggested by Engel and Engel (1964), this would imply that the greenstone belts have formed by an accretionary process from some smaller and very ancient original sialic nucleus. If this were the case, then a decrease in age of the greenstone belts, proceeding away from the first-formed, oldest one would be expected. Although the age data on greenstone belts is extremely limited, it would appear that no such systematic age change is evident within the greenstone belts of any one particular shield area.

Another process visualized by the authors and considered to be a more likely explanation involves the development of roughly evenly-spaced, strongly orientated, parallel downwarps or fault-bounded troughs on an unstable, thin, primitive sialic crust (see Figure 4a). In these areas, vast amounts of lava accrued to form the basal volcanic sequences of the greenstone belts. This was followed by sedimentation in the troughs. It is possible that lavas were also extruded in the areas between the elongate downwarps, but the amount was probably much less (see Figure 4b). It is conceivable, therefore, that, during the initial magmatic event, almost the entire primitive crust was covered by lava, albeit rather thinly in the areas between the deep troughs. Subsequent flooding by younger granites apparently obliterated much of this material, but the deep accumulations of lava in the orientated elongate troughs have generally been preserved to form the present greenstone belts (see Figure 4c).

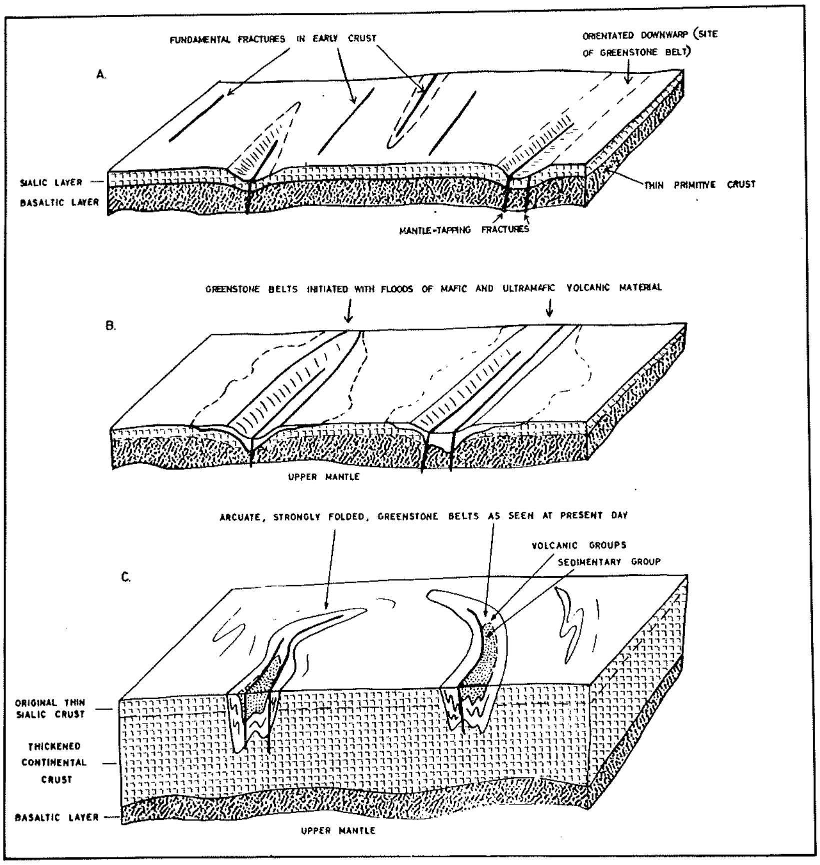

Figure 4 : Diagrammatic illustrations showing the suggested evolution of greenstone belts.

The persistence of a strong regional trend of greenstone belts in most early Precambrian shield areas suggests some fundamental control over their initiation – possibly an early Precambrian fold or fracture pattern formed across the primitive crust as a result of rotational forces. Whatever speculation arises from the problems of the early evolution of the earth's crust, the greenstone belts represent the first clearly defined or decipherable geological event on that crust, and as entities, they appear to be unique to the early Precambrian.

B. STRATIGRAPHY OF THE GREENSTONE BELTS

A characteristic assemblage or association of rock-types typifies the stratigraphy of the early Precambrian greenstone belts. The marked stratigraphical similarities produced during this early chapter in the earth's history have never been reproduced fully in later times, although there are areas, particularly in the more recent geosynclinal and island arc environments, where the rock successions are very similar to those of the greenstone belts.

An attempt has been made to compare the volcanic rocks in the greenstone belts with the ophiolites, or initial magmatic phase, of a geosyncline or island arc, while the sedimentary successions have been equated with the flysch and molasse assemblages, also of geosynclines (Anhaeusser et al, 1967). The validity of this comparison is open to criticism; what is quite clear, however, is the fact that the rocks must have been deposited initially in very deep, probably subsiding troughs that eventually allowed for infilling by enormous thicknesses of both volcanic and sedimentary material. A thickness of approximately 100,000 feet has been reported from Western Australia (McCall, 1969). A comparison of the various lithologies found in schist belts allows the broad generalization to be made that the rock-types can be grouped into an early, essentially volcanic phase (initial magmatic phase) and a later, essentially clastic sedimentary phase. Taking this classification a step farther, the predominantly volcanic phase has been subdivided into an Ultramafic Group and a Greenstone Group, while the sedimentary phase has been listed as the Sedimentary Group (see Table 1).

Rock-types commonly associated with the volcanic phase vary somewhat from one belt to the next, yet the differences never allow the belt to lose its fundamental identity. The volcanics include ultramafic (Viljoen and Viljoen, in preparation), mafic, intermediate and salic lavas, with the mafic suite predominating. Specific rock-types encountered include peridotites, tholeiitic basalts, andesites, dacites, rhyolites, and porphyries, together with a great variety of pyroclastics (tuffs, ignimbrites, breccias, and agglomerates). The volcanics frequently display pillow structures, but closely associated, massive lavas are invariably present and often well-represented. Subordinate, interbedded sedimentary horizons are characteristically associated with the volcanics. Often occurring as apparently intrusive, sill-like bodies, mostly within the volcanic assemblages of greenstone belts, are a wide variety of ultramafic rock-types. They vary in composition from bodies consisting entirely of dunite and peridotite or their serpentinized products, to highly differentiated varieties consisting of one or more of the following rock-types: dunite, peridotite, pyroxenite, gabbro, norite, and anorthosite.

The exact age of intrusion of these bodies is nowhere truely defined as very often they are fault bounded and appear to have been tectonically moved, occurring frequently as lensoid pods. In most cases, however, they occur intimately associated with the volcanic rocks of the initial magmatic phase and the writers' are of the opinion that the majority of this type of body were emplaced before the deposition of the overlying Sedimentary Group. They are thus largely contemporaneous with the initial vulcanism.

A number of mafic differentiated bodies often occur in the granitic terrains surrounding greenstone belts but evidence is generally not definitive enough to ascribe them to the initial volcanic phase of the greenstone belts themselves. It is likely that they may

TABLE 1

TABLE SHOWING THE PRIMARY LITHOLOGIES, METAMORPHIC DERIVATIVES, DEPOSITIONAL FEATURES, AND FREQUENCY OF OCCURRENCE OF ROCKS DEVELOPED IN GREENSTONE BELTS

Group	Primary Lithological Types	Frequency of Lithological Types	Depositional Features	Metamorphic Derivatives
SEDIMENTARY GROUP Predominantly sediments - subordinate volcanics				Characterized by mineral assemblages typical of the greenschist facies with locally developed amphibolite facies assemblages
	(a) Essentially shallow water sediments Minor development of volcanics and pyroclastics. Banded ironstones, jaspilites, cherts, limestones, sub-greywackes, shales, quartzites (clean and impure quartzites, felspathic and calcareous quartzites). Boulder beds, conglomerates, grits, arkoses.	All sediments listed are frequently encountered. Chemical precipitates often present but may be poorly developed or absent entirely.	Pillows, amygdales, etc. Chemical precipitates - precipitation of limestones chemically and by organic agencies. Cross-bedding, ripple marks, graded beds, mud-cracks, some turbidites. Channel conglomerates, floor conglomerates. Intraformational slumping in turbidite type sediments and banded ironstones	Schists and phyllites with quartz, muscovite/sericite, biotite, chlorite, tremolite, cordierite, garnet, chloritoid, paragonite, pyrophyllite, the Al_2SiO_5 polymorphs, staurolite, grunerite, etc. in various combinations
	(b) Possibly deeper water sediments Minor development of volcanics-tuffs, agglomerates, lavas.	Usually present	Pillows, flow lines, amygdales - water-worked pyroclasts.	
	Banded ironstones, jaspilites, cherts.	Usually present	Chemical precipitates - laminites.	
	Greywackes, shales, conglomerates, grits.	Usually present	Turbidite structures (graded beds, rhythmic layering, convolute beds, current marks, erosion channels, channel gravels, etc).	Quartz-sericite-chlorite schists and phyllites + Al_2SiO_5 polymorphs, chloritoid, etc.
GREENSTONE GROUP Predominantly volcanics and pyroclastics-subordinate sediments	Banded ironstones, jaspilites, cherts	Often present	Essentially chemical precipitates	Banded ironstone retains structure but Fe amphiboles and chlorites develop and quartz and magnetite recrystallize.
	Carbonaceous shales and cherts, graphitic sediments.	Often present	Chemical precipitates - laminites	Crystalline limestones + tremolite, quartz, etc.
	Mafic and salic tuffs and agglomerates, ash beds.	Often present	Water worked tuffs, agglomerates	
	Siliceous and mafic greywackes, conglomerates, quartzites, limestones, grits (sediments interlayered with volcanics).	Often present Limestones sometimes present	Turbidite structures (graded beds, convolute beds, flute casts, current marks, rhythmic layering etc.) Chemical precipitates, precipitation by organic agencies.	Quartz-sericite schists, phyllites, etc.
	Minor development of ultramafites	Sometimes present		Serpentinite; talc, tremolite schists.
	Porphyries Rhyolites Dacites Andesites Basalts (tholeiitic)	Often present Sometimes present Often present Always present - abundant Often present	Massive, jointed. Pillow structures may be present in rhyolitic and dacitic lavas (amygdales, spherulites, etc.) Prolific development of pillow structures, amygdales, gas cavities, spherulites, variolites, flow lines and massive flow centres.	Rhyolites often retain original texture but recrystallize (quartz-albite-hornblende/actinolite) Dacites where sheared = chlorite or talc chlorite schists. Often retain original texture but felspar altered to sericite and clinozoisite. Mafic minerals, amphibole/chlorite. Massive carbonated "greenstones", actinolite-chlorite schists. Actinolite, hornblende schists.
ULTRAMAFIC GROUP Predominantly volcanics and pyroclastics-subordinate sediments	Siliceous, aluminous tuffs, agglomerates. Minor interlayered sediments (cherts, graphitic shales, banded ironstones, fine grained quartzites).	Often present but may be poorly developed or absent entirely	Bedded tuffs and agglomerates. Chemical precipitates - laminites.	Quartz-sericite schists, aluminous schists (andalusite, kyanite, sillimanite, cordierite, chloritoid - staurolite) garnetiferous schists and quartzites.
	Tholeiitic basalts (lava)	Usually present	Prolific development of pillow structures, gas cavities, amygdales, flow lines, etc. Also massive sills.	Actinolite schists + hornblende, chlorite, albite, quartz, stilpnomelane, epidote, zoisite, garnet, and sometimes diopside.
	Dunites, peridotites (some extrusive) pyroxenites, gabbros, anorthosites	Not often encountered. Absent in many greenstone belts ?	Pillows developed in some ultramafic lavas. Generally massive or pseudostratified, layered.	Serpentinite, serpentinite schists, talc-tremolite schist, tremolite-chlorite schist.
	Early crust - in part granitic?			

represent intrusive bodies of a much younger age.

The sedimentary phase displays a wide array of rock-types, with greywackes, shales, banded ironstones, jaspilites, and cherts being particularly characteristic. In addition, conglomerates, breccias, quartzites, sandstones, and siltstones, are encountered. The seemingly simple lithologies of both the volcanic and the sedimentary phase are invariably complicated by an accompanying wide variety of metamorphic derivatives. Table 1 has been compiled to demonstrate concisely what rock-types may be expected in a typical greenstone belt. In addition to the primary lithologies listed, the table displays the frequency of occurrence of the various rock-types and the depositional features (sedimentary and volcanic structures) that are characteristically developed. Metamorphic derivatives are listed in a separate column.

Some of the typical associations that may be expected in the early Precambrian belts are well-represented in the Rhodesian greenstone belts (Swift, 1961; Macgregor, 1951) and in the Barberton Mountain Land, which forms one of the best-developed and best-preserved remnants of early Precambrian strata in Southern Africa (Visser et al, 1956; Anhaeusser et al, 1967).

Lying at the base of the Swaziland Sequence of the Barberton Mountain Land is an exceptional development of volcanic rocks comprising basic pillow lavas, ultramafites, and associated siliceous sediments. Known locally as the Onverwacht Group, it attains a thickness in excess of 50,000 feet (Viljoen and Viljoen, in preparation). Particularly prominent in the Barberton belt are ultramafic successions making up a large proportion of the lower half of the Onverwacht Group.

However, the ultramafic assemblage of rocks is not always encountered in the greenstone belts, particularly those in Canada. Their presence, generally towards the base of the volcanic pile, suggests that the ultramafic rocks initially had access to the surface because of the thin crust and the existence of deep crustal fractures. Associated with the ultramafic rocks are basaltic pillow lavas together with subordinate horizons of interbedded sedimentary rocks. The sediments associated with the early volcanics in the Barberton belt consist of distinctive, siliceous members, together with salic tuffs and occasional thin, carbonaceous chert horizons. The ultramafics, on metamorphism, are converted to a great variety of rock-types, including serpentinites, talc, tremolite, and antigorite schists. The associated mafic lavas alter to metabasalts containing mainly actinolite, hornblende, and lesser amounts of quartz and sodic felspar. Chlorite and tremolite-actinolite are more common farther away from the granite contacts (see Table 1).

As mentioned previously ultramafic rocks are generally absent in the early Precambrian greenstone belts of Canada. Instead, andesitic volcanics appear to be particularly prominent (Stockwell, 1957; Wilson, 1962; Boyle, 1961; Wilson, 1965). In Western Australia examples of early Precambrian assemblages containing ultramafic rocks and other typical greenstone assemblages and associated sediments can be found in the Yilgarn and Pilbara Blocks (Prider, 1965; Horwitz and Sofoulis, 1964; Ryan, 1964; Ryan and Kriewaldt, 1964). Similar greenstone assemblages, consisting of mafic volcanic rocks, often exhibiting well-developed pillow structures, are known in the Dharwar System in the Mysore State of India. Also developed in this early Precambrian succession are intercalated bands of quartzite, iron formations, and limestones (Pichamuthu, 1957).

The typical greenstone assemblage of the early Precambrian belts are particularly well-displayed in the Bulawayan sequence of Rhodesia (Macgregor, 1951) and in the Onverwacht Group of the Barberton Mountain Land (Viljoen and Viljoen, 1967). In the Rhodesian belts, the formations consist of a monotonous succession of volcanic rocks, mainly of mafic composition, but include also wide tracts of andesitic breccias and lavas with which dacites and rhyolites are sometimes associated. Also characteristic is the occurrence of pillow structures in the basalts. Subordinate sediments often occur interbedded within the volcanics, and are generally thin, but can be traced almost continuously for great distances. Jaspilites and banded ironstone form conspicuous, resistant outcrops, and greywackes, conglomerates, and, less often, limestone, phyllite, and granular quartzite may occur. In the Barberton belt, the uppermost division of the Onverwacht consists of a similar assemblage of pillow basalts, with numerous zones of andesitic, dacitic, and rhyolitic lavas, the last-mentioned frequently associated with persistent, narrow, well-banded, often carbonaceous, chert horizons.

Available chemical analyses from the least metamorphosed areas of a number of greenstone belts indicate that most of the basalts have tholeiitic affinities. Although the major proportion of volcanics in greenstone belts are of basaltic or andesitic-basaltic composition, the rather widespread occurrence of andesites and, to a lesser extent, dacites, rhyodacites, and rhyolites, indicates that the calc-alkaline series of volcanic rocks appears to be important in early Precambrian sequences. Evidence of alkali basalts or the alkali basalt line of descent, and their metamorphic derivatives, appears to be lacking. Likewise, spilitic rocks, which are often associated with the volcanic piles of younger orogens, are not developed. Soda-plagioclase is, however, well-developed in many of the amphibole-bearing metabasalts. This merely indicates a metamorphic effect, and does not imply that the original unmetamorphosed rock was soda-rich. The absence of blueschist facies metamorphism (glaucophane schists) suggest that spilitic rocks were not developed in the greenstone belts.

Many of the volcanic structures observed in the ancient greenstone belts are of importance in the understanding of the processes involved in the extrusion of subaqueous lavas. Particularly significant is the association of pillow lavas, massive lavas, and mafic tuffs. Pillow lavas and mafic tuffs, although often conspicuous, are generally not as widespread in their development as the massive lavas. It appears likely from this that lava, extruding into water, may have formed a large pile of pillows, together with associated mafic tuffs and agglomerates, probably of the palagonitic type. This volcanic accumulation may have acted as an effective seal or carapace, thereby protecting later eruptions from aqueous chilling. Subsequently introduced lava would then have the appearance of massive sills.

Most of the sediments derived from volcanic rocks occurring in greenstone belts appear to be varieties of tuff. Many of these are of interest in that they have formed subaqueously or have been reworked by water. In addition, pillow breccias and their associated aquagene tuffs, similar to those described by Carlisle (1963), are present. In many cases, these have probably been called volcanic breccias. It is also apparent that subaqueous ash flows or ignimbrites, similar to those described by Fiske (1963), are present in many of the early Precambrian belts.

Following the initial volcanic episode, the subsiding troughs acquired vast accumulations of sedimentary material which was laid down sometimes conformably and in other instances unconformably, on the earlier volcanic rocks, and subsequently infolded with them. The sedimentation style was controlled by the depth of the basin. Usually, the earliest sediments consist of greywackes, argillites, banded ironstones, cherts, jaspillites, and grits. Volcanics are less common, but can occur as contemporaneous, intraformational lava and tuff horizons (see Table 1). Sedimentary structures, such as those characteristic of turbidites (graded-bedding, convolute-bedding, current-marks, flute-casts, etc) are of use in establishing the environment and style of deposition. The rocks are essentially clastic, although chemical precipitates (cherts, jaspilites, banded ironstones) also occur in this sedimentary group. The later sediments consist essentially of conglomerates, quartzites, sandstones, sub-greywackes, siltstones, and shales. Once again volcanic rocks are only rarely present. Chemical precipitates, including banded ironstones and limestones (usually thinly-developed), may occur, but are not common.

Examples of assemblages of these typically shallow-water sediments (cross-bedding, ripple-marks, mud-cracks, etc) are the Moodies Group of the Barberton belt and the Shamvian Group of Rhodesia.

In the Barberton Mountain Land, a well-displayed cyclicity of volcanic and sedimentary units is evident (Anhaeusser et al, 1967). In the volcanic sequence, ultramifites and basalts alternate in a cyclic manner. The mafic lavas are followed upwards by salic tuffs and agglomerates and individual cycles are often capped by cherts. Similarly, in the predominantly sedimentary successions, there are cycles, each of which shows a size variation from coarse material at the base to finer material at the top.

Attention has recently been focused on some of the carbonaceous shale and chert horizons of the early Precambrian sedimentary assemblages, particularly those in the Barberton belt in South Africa. Here, primitive life-forms, akin to present-day bacteria and algae have been found and described (Barghoorn and Schopf, 1966; Pflug, 1966). Hydrocarbons and chemical substances similar to the type produced by living organisms have also been reported (Hoering, 1964-65; Oró and Nooner, 1967; Bitz et al, 1967; Schopf, 1967; Schopf et al, 1968). These ancient sediments, recording evidence of some of the earliest fossil life on earth, are at present receiving considerable attention.

C. GRANITIC ROCKS OF THE CRATONS

The vast areas of granitic rock which surround the greenstone belts and form a major part of the Precambrian cratonic areas, are clearly a very important, though frequently neglected, aspect of these cratons. The greenstone belts occur as synclinal remnants in a granitic terrain which generally constitute some of the thickest and most stable parts of the continents (see Figure 2). These granites surround, and often intrude, the greenstone belts, causing deformation and metamorphism. In some places, the granite episodes completely obliterate the greenstone belts, so that only metamorphosed vestiges and xenoliths remain. Thus, the granite episode, or, more likely, episodes, in the early Precambrian constitute an important geological event, intimately related to which are the fundamental questions of the differentiation of the earth's mantle and the development of a substantial sialic crust from a thinner, earlier crust. The probable nature and origin of the early crust have already been discussed. Here, consideration will be given to the mode of origin and history of emplacement of the great variety of granitic rocks which are such a striking feature of the shield areas.

Although little detailed information regarding the granitic rocks of the shield areas exists, three main categories appear to be present. A complex array of migmatites and banded gneisses, together with more homogeneous granite phases, constitute some of the oldest of the granitic rocks. A second distinctive type of granite forms circular or elliptical diapiric bodies. Thirdly, a series of potash-rich, coarse-grained, often porphyritic granites intrude and interrupt all earlier-formed trends and structures. It is emphasized that any account of the granites of the early Precambrian shield must be subject to reservations arising from the general paucity of work carried out on them, and there is no doubt that the picture is rather more complex than this account does portray.

The origin of the migmatites and gneisses remains a most perplexing one, and it has been argued that at least part of this material constituted a basement or crust on which the volcanic assemblages of the greenstone belts were deposited. As far as the authors are aware, however, there are no reports of greenstone lying unconformably on an older, contorted migmatite. Instead, a zone of intrusive granite invariably occurs at the contact. It has been suggested that the migmatite, and particularly that with mafic streaks and inclusions, might represent vestiges of a now completely granitized greenstone belt belonging to a previous cycle. There is evidence that at least some of the migmatite does, in fact, represent the granitized equivalents of nearby greenstone belts. This would imply that some of the gneisses and migmatites may have originated in a manner very similar to those in the younger mobile belts (see later), but that they formed at a much earlier stage. In areas where migmatites and gneisses are developed, strong indications of widespread mobilization and potash metasomatism are usually conspicuous. This is accompanied by metamorphic differentiation resulting in the formation of potash-rich, light-coloured, felsic bands, and darker, more femic bands. This process appears to have played an important part in the formation of a distinctive banded gneiss. These gneisses are often strongly contorted and afford evidence of flowage folding, indicating that the whole mass was in a very plastic state. Within this type of terrain, large areas of complete local homogenization (homogeneous granites) may be encountered. These granites are generally gradational into the more strongly banded variety, and it has been shown in Swaziland by Hunter (1965) that, proceeding upwards, a migmatitic and gneissic assemblage grades into a homogeneous, potash-rich, high-level, "hood-zone", characterized by numerous pegmatites. All rocks in a particular region, ranging from banded gneisses to homogeneous granites, which have been involved in any widespread mobilization and metasomatism of this type, give similar radiometric ages.

The circular or elliptical granodioritic diapiric plutons are widely developed in the early Precambrian cratons and are the most distinctive of the granite types. As yet, their relationship to the banded gneisses and migmatites discussed above is not clear, although in some areas they appear to be transitional. These bodies, which are amongst the oldest granitic rocks encountered, are characterized by a low potash : soda ratio, and a poorly developed associated pegmatite phase. This type of granite is usually responsible for the formation of the peculiar arcuate greenstone tongues which form such a striking feature of the shield areas. Their fundamental rôle in the establishment of the early Precambrian structural pattern (see Figure 5), was first recognized by Maufe et al, (1919) in Rhodesia. Macgregor (1951) introduced the idea of "gregarious batholiths" to explain the structure of the Rhodesian craton. However, the diapiric granites, although clearly having incorporated material from the greenstone belts, either as xenoliths or as diffuse, assimilated schlieren, probably formed by the slow upwelling and forceful emplacement of discrete and largely plastic granitic masses.

The resulting relationship between granite and greenstone belts thus appears to be a response to gravitational adjustments during the upwelling of granite and the concomitant downsagging of the greenstone belts. These granites appear to be responsible for most of the thermal, as well as the dynamic, metamorphism of the greenstone belts into which they intrude, and they are also the cause of the distinctive arcuate structures in the latter. Evidence of this is afforded by the nature of the foliations and lineations in the metabasalts which parallel those in the foliated margins of the granites. The foliation in the granites is caused by the alignment of platy minerals, and is accentuated by aligned, metamorphosed, mafic xenoliths (Anhaeusser et al, 1967). Towards the central part of the diapiric plutons, the foliation becomes less pronounced, and may disappear (see Figure 6). The low-grade metamorphism caused by these granites, seldom higher than amphibolite facies, and the relatively narrow contact aureoles, seldom more than 2,000 feet wide, are noteworthy.

It should be pointed out that while these bodies, which can vary in size from less than a mile to several tens of miles in diameter, are responsible for the local structures in their immediate environment, these are frequently superimposed onto some earlier trend. This earlier trend in a greenstone belt tends to follow the regional grain, or trend, of other greenstone belts within any particular craton, as suggested previously.

Finally, a series of generally smaller, often circular, younger, high-level granite plutons occur on the cratons as scattered, apparently randomly distributed bodies. Several phases of this type of late, high-level granite may be present. These granites are potash-

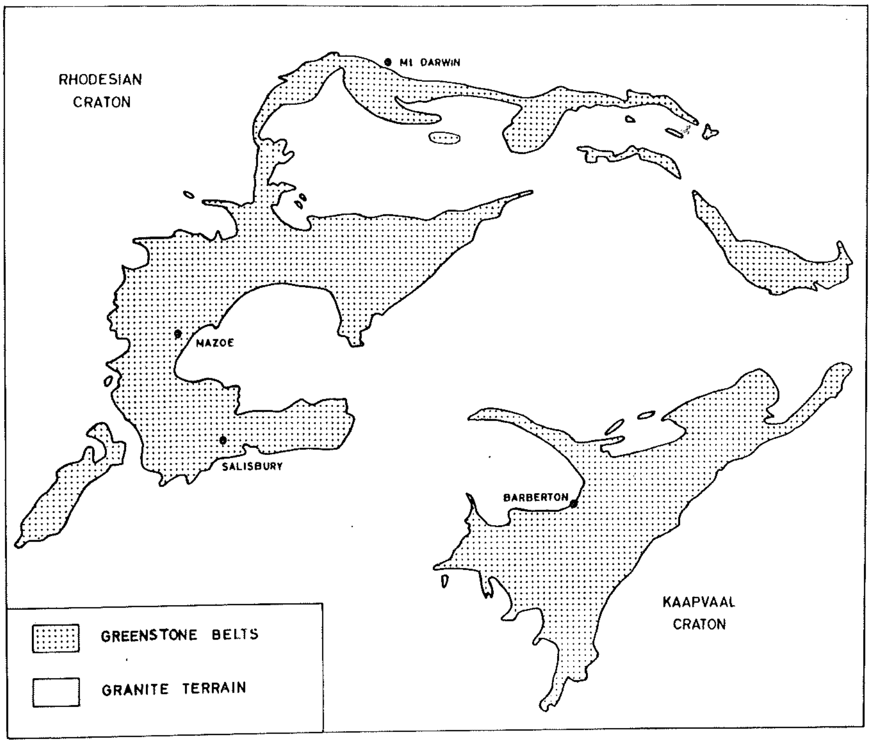

Figure 5 : The greenstone-granite pattern of the cratonic nucleii illustrated by the Mt. Darwin-Mazoe-Salisbury greenstone belts of Rhodesia and the Barberton Mountain Land of South Africa.

rich, usually rather coarse-grained, porphyritic, homogeneous, and non-foliated. Unlike the granites discussed previously, they have generally caused only local structural disturbance during their emplacement, owing to the fact that they were probably intruded into an already stable, relatively cool, cratonic environment. They characteristically cause abrupt truncation of earlier formed structures and trends, and usually displace or eliminate the formations into which they intrude. Very narrow contact aureoles characterize this type of granite intrusion, suggesting that emplacement took place at high crustal levels. Concentric, en-echelon faults and fractures may surround these intrusions. The various granite-types mentioned above, and their relationship to the greenstone belts, are diagrammatically portrayed in Figure 6.

The concept of geosynclines, with their attendant orogeny, metamorphism, and granite generation, cannot be applied to the early Precambrian shields. A fundamental aspect of the granites of the shields is that their emplacement appears to be the direct cause of the strong folding of the supracrustal rocks of the greenstone belts. The granites are not the result of, nor do they in any way appear to be associated with, the type of orogeny and consequent granite formation of a geosyncline in the classical sense. The low

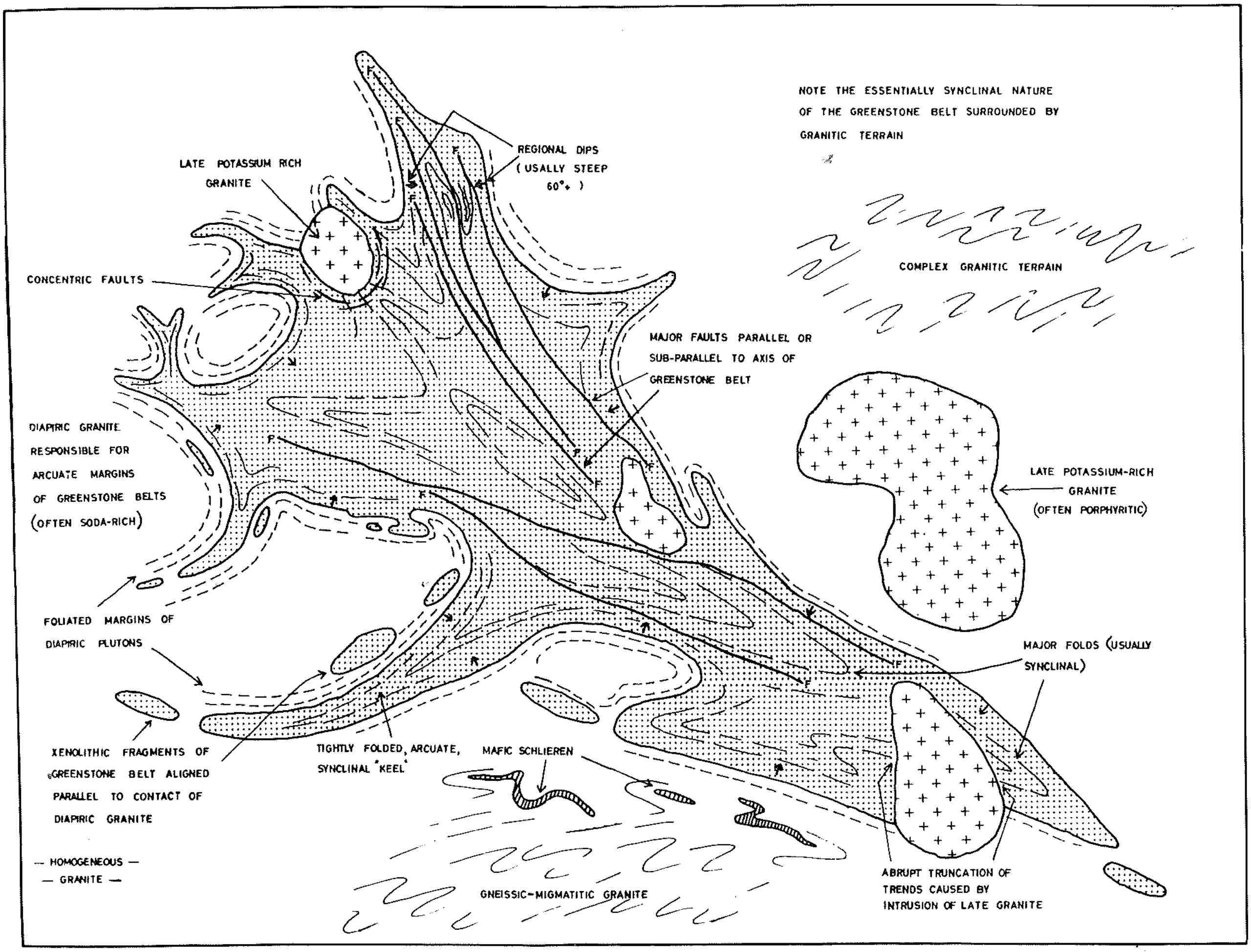

Figure 6 : Hypothetical and diagrammatic model illustrating the distinctive and characteristic features of the early Precambrian greenstone belts and associated granites of the cratonic nucleii.

grade of metamorphism of the greenstone belts also clearly precludes their ever having been at any depth within the crust — certainly not in the zone of anatexis, which would be expected if they represent part of the "root-zones" of orogenic belts derived from geosynclines. It has been suggested (Roering, 1967) that granitic material was added to the crust in very early Precambrian times directly from a differentiative process in the upper mantle, without reference to any orogenic zones. It appears that this process of anorogenic granite addition may have ceased to operate in younger geologic times (Roering, 1967), or, if it was in operation, it is suggested that the result was a sialic underplating of the continents with no visible surface manifestations.

Independently derived geochemical and geophysical data suggest a partial or complete melting of the outer earth early in its history (Engel, 1965). This event would greatly have accelerated the differentiation of mantle and crust by permitting the more volatile constituents, including all the granite-forming elements, to rise towards the surface. This early thermal event may thus have played an important rôle in the formation of the early Precambrian granites, and was apparently never repeated again in subsequent geological times. The upward streaming of sialic constituents, which was preferentially concentrated in continental areas, as opposed to oceanic areas, remains one of the most enigmatic problems of earth science.

D. STRUCTURE AND METAMORPHISM OF THE GREENSTONE BELTS

The large-scale structure of the greenstone belts, and its relationship to pre-existing structural patterns and the granites has already been discussed — the large arcuate structures, and the large-scale folds with axes more-or-less parallel to the axes of the greenstone belts being outstanding features. Many of the large folds developed in greenstone belts are synformal. Frequently two synformal structures occur together, without a complementary antiform, and the adjacent limbs of these synforms appear to be separated by a dislocation. This is suggestive of tectonic sliding having occurred (Fleuty, 1964, for definition of "tectonic slide"), and further supports the concept that the structure of the greenstone belts has been a response, at least partly, to essentially vertical movements. Obviously, the large structures of these belts will tend to parallel the long direction of each belt and be modified by the diapiric granites which cause the arcuation of the greenstone belts.

Some of the more distinctive characteristics of the early Precambrian greenstone belts are the low grade of metamorphism, and the preservation of original volcanic and sedimentary features, especially away from the granite contacts. The structural and metamorphic features are typical of so-called supracrustal domains, and they indicate the preservation of crustal fragments (cratons) from the early Precambrian which do not appear to have suffered very much erosion either, at least as far as significant erosion down to a lower crustal level is concerned. Two structural elements characterize all early Precambrian greenstone belts, and these are a penetrative schistosity which typically displays a steeply plunging "stretch" lineation on schistosity surfaces, and non-penetrative crenulation cleavages (see Turner and Weiss, 1963, for definition of penetrative and non-penetrative). Development of schistosity and cleavage is dependent on the suitability of lithological types involved in deformation, and this selective factor results in the sporadic distribution of schistosity and cleavage which is so typical in the greenstone belts. Thus, rocks which develop platy minerals during metamorphism, and in which quartz is either poorly represented or absent, tend to form schists and phyllites, whereas quartz-rich metasedimentary rocks, limestones, banded ironstones, volcanic porphyries and agglomerates, and also certain greenstone lavas tend to remain massive. Another factor which influences the development of schistosity in these rocks is their proximity to granite intrusives. It has frequently been observed that schistosity tends to be more consistent and intense at the margins of greenstone belts and around diapiric granite bodies and plutons intrusive into the belts. That the upwelling of granite masses produced the steeply plunging lineation on schistosity surfaces, and an associated metamorphic fabric, seems to be reasonably well-established, but the concomitant downsagging of the greenstone belts must also be considered as a contributing, if related, factor. The lineation is produced by the alignment of acicular minerals and the stretching of quartz-rich lenses, pebbles, pillows, amygdales, spherulites, and even felspar phenocrysts in the volcanic rocks, and it is regarded as being parallel to the direction of movement in these rocks. Flattening parallel to the schistosity is related to compression caused by the emplacement of granite at high levels. It follows that the schistosity need not be related to an early period of folding, and that regional compression over the whole craton need not be invoked to explain the structures of typical greenstone belts. In some belts, a notable example being Barberton in South Africa (Ramsay, 1963; Roering, 1965), slaty cleavage which is axial planar to large-scale folds has developed subsequent to the formation of the schistosity, but this does not appear to be common, and is unrelated to the crenulation cleavages which form still later. Whereas the slaty cleavage is discordant to bedding in fold closures, it is a noteworthy fact that the schistosity is usually parallel to bedding throughout. The crenulation cleavages are related to various types of plications formed during later periods of folding, and are axial planar to these folds.

The deformation in greenstone belts is thus complex, although the resultant structures are well-preserved, and it may vary in its intensity, depending on position in the belt and the lithologies involved. Kinematic interpretations of structural data based on stress fields related to regionally directed compression must be regarded with caution because of the local factors involved in the structural evolution of each individual greenstone belt. Any structural analysis of such a belt must take all such factors into consideration. Faults frequently develop parallel to the long axes of these belts, and usually display both horizontal and vertical movements. These faults accentuate the early weaknesses which controlled the sites of volcanicity and sedimentation in these belts. Low-angle thrusts are rare, if not altogether absent. Certain types of strike faults resemble slides (Fleuty, 1964) and may be gravity responses, with dislocation following the emplacement of granite and the accompanying downsagging of the greenstone belt.

Low-grade greenschist facies metamorphism (Winkler, 1967; Hietanen, 1967) is typical of the major part of greenstone belts. The metamorphic derivatives of the volcanic and sedimentary rocks of typical greenstone belts are listed in Table 1. There is an intimate relationship between metamorphism and deformation, and the sequence is usually of 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. Local increases in the grade of metamorphism may occur at the edges of greenstone belts, or around intrusive granitic stocks within the belts themselves. The usual effects are a coarsening of textures towards the margins of the belts and the formation of hornblende, instead of actinolite in mafic volcanic rocks, together with the formation of andalusite, kyanite, and sillimanite in aluminous pelitic rocks. The higher grade metamorphic aureoles, so produced, are usually narrow (rarely more than 2,000 feet), and this telescoping of facies may be due to rapid cooling of the granites as they reach higher levels in the crust. However, although it can often be demonstrated that these metamorphic aureoles form as a result of later granites, and are therefore overprinted on the regional metamorphism, it is by no means certain that the regional metamorphism itself, was primarily a result of heat from the granite. For example, it is often observed that certain higher grade metamorphic zones coincide with the most sheared parts of the greenstone belts. However, these are often along the margins of belts, in contact with intrusive granites, so that, while heat produced by shearing may have created a higher grade of metamorphism, this would be difficult to distinguish from metamorphism caused by heat from the granite. If there was a thin crust at the time of formation of the greenstone belts the heat flow from the mantle would be relatively high and may itself have been responsible for the early regional metamorphism. The high-grade aureoles may not be developed although uniform greenschist facies metamorphism prevails throughout most belts. Changes in the physico-chemical conditions of metamorphism may also have resulted from the shearing.

There is, as mentioned previously, a notable lack of metamorphism of the glaucophane schist facies in the greenstone belts, which appears to be related to a lack of soda-rich volcanic rocks of the spilite-keratophyre association, rather than to peculiarities of the metamorphic environment and conditions of metamorphism.

Metasomatic effects in the greenstone belts are reflected in the carbonation (propylitization) of the mafic and intermediate volcanic rocks near quartz veins associated with gold mineralization, and, in many belts, boron metasomatism related to granite intrusion, produces concentrations of tourmaline in quartz veins and adjacent wall-rocks. The lack of granitization has been mentioned, and in belts where granitization has occurred, it is usually related to later, superimposed tectonothermal events impinging on the cratonic areas.

E. ECONOMIC IMPLICATIONS

The early Precambrian greenstone belts of the Precambrian cratonic areas have long been sources of economically exploitable mineral deposits. Gold, has largely been responsible for the careful mapping and detailed study of the rock assemblages variously termed "gold belts" or "greenstone belts". Most of the "primary" gold deposits of the world are confined to these greenstone belts, and appear to be related to the greenstone themselves. In general, it can be demonstrated that, where there are no greenstones developed, there is also a concomitant lack of gold mineralization. Although gold and silver are generally the most valuable metals to be found in these belts, there is nevertheless, a host of other minerals of considerable importance, the optimum development of which appears to be restricted mainly to the greenstone remnants of the major shield areas of Canada, Australia, India, and Africa. Not the least important of these are the chrysotile asbestos deposits, providing the bulk of the world's supply of this commodity. The asbestos deposits are confined to ultramafic host-rocks that have invariably undergone alteration to serpentinite. Some of the world's most valuable chrome-ore deposits also occur in the ultramafites, and important nickel mineralization is known in these rocks. The same ultramafites also act as host to magnesite and talc deposits.

The Precambrian banded iron formations, including chemically precipitated jaspilites and ferruginous quartzites of clastic sedimentary origin, are a source of some of the highest-grade iron ore deposits yet discovered, and also form vast reserves of low-grade iron ore. Much of the high-grade ore is due to localized secondary enrichment of itabirites and banded ironstones resulting in extensive recrystallization and concentration of the iron formations. The persistent occurrence of the typical early Precambrian iron formations and ferruginous cherts with volcanic rocks, greywackes, and shales suggests that there is a genetic relationship between these rocks and volcanism. Volcanic activity appears to have contributed both the iron and the silica to these formations (Gross, 1965). Important occurrences of metallurgical-grade manganiferous ore are also associated with the early Precambrian sedimentary banded iron formations.

Other important base metals often found occurring in the greenstone belts are ores of antimony (stibnite), mercury (cinnabar), copper (chalcopyrite), arsenic (arsenopyrite), tungsten (scheelite), lead (galena), sulphur (pyrite, pyrrhotite), vanadium (titaniferous magnetite), zinc (sphalerite), and molybdenum (molybdenite). Silver, copper, lead, zinc, antimony, tungsten, pyrite, and arsenic are usually produced as by-products of gold mining. Non-metallic minerals of economic importance, apart from the chrysotile asbestos, talc, and magnesite, mentioned previously, are deposits of barytes and the refractory ores, sillimanite, kyanite, andalusite, and corundum. In addition to these minerals, there is a wide variety of ores associated with the granites and pegmatites that so often intrude the greenstone belts. The more important of these are tin (cassiterite), tantalum and niobium (columbite-tantalite), beryllium (beryl), and lithium (spodumene, amblygonite, and lepidolite).

The origin of the gold and related mineralization in greenstone belts has generally been ascribed to pneumatolytic products of invading granitic magmas. All too frequently, convenient "igneous emanations" and "hydrothermal solutions" have been called upon to provide a source for the mineralizing solutions. Sullivan (1948) and Knight (1957) were among the first to deviate from the popular theories of ore generation, and laid the foundations of the "source bed concept". More recently, Oftedahl (1958), Marmo (1961), Stanton (1959), King (1965), McDonald (1967), and others have suggested that many sulphide ore deposits are the result of the palingenetic reconstitution of sulphides derived from within a particular rock-type. Boyle (1959, 1961) was able to demonstrate that gold-quartz deposits of the Yellowknife district in Canada were derived, by lateral and vertical secretion of volatiles and other constituents, from the series of rocks in which they occur. Evidence is therefore gradually mounting to suggest that the origin of gold and sulphide mineralization was more a result of the mobilization of chalcophile elements, inherent in the original mafic (tholeiitic) lava of the greenstone belts, involving processes accompanied by strong thermal gradients, set up by the invading granitic magmas. Thus, many epigenetic hydrothermal deposits may, in fact, have been formed contemporaneously with their enclosing or neighbouring rocks, and may have attained their present hydrothermal-like characteristics solely through the agencies of metamorphism and metasomatism.

Chromite in early Precambrian greenstone belts can usually be related to the the magmatic differentiation of the mafic and ultramafic rocks involved, whereas most of the non-metallic minerals are related to later metamorphism (asbestos, talc, kyanite, etc). Nickel is considered to be inherent in mafic and ultramafic rocks which occur in the greenstone belts, and economic concentrations of the metal also appear to depend on the availability of a later heat source (usually granitic intrusive) to mobilize the metal. Furthermore, the later intrusive granites, which typically pierce the greenstone belts as small stock-like bodies, create faults and tension fractures around them, which may accommodate certain ore bodies, such as nickel, copper/nickel, and gold (see Figure 6).

The particular structural style typically associated with the greenstone belts also played an important rôle, in that it provided suitable dilatant zones of low pressure (faults, fractures, fold, etc) into which the mineralized solutions could migrate. The structural control of all types of mineralization associated with the greenstone belts is now a well-established fact. Clearly, an intimate knowledge of the structure of any one belt is essential if any degree of success in the explorational development of ore deposits is to be hoped for. The occurrence of mineralization in these belts is erratic, but often highly rewarding, and can be narrowed down to several controls in addition to structural. These include sedimentary and chemical influences responsible for the iron-formations, barytes occurrences and limestone deposits, and the stratigraphic controls which allow particular rock-types to act as natural traps for any mineralization. Siliceous horizons, such as cherts and quartzites, act as competent units, and feature prominently on the list of rock-types that may be regarded as being of influence stratigraphically. The competent nature of these rocks not only provides suitable structures, but also acts, at times, as impenetrable barriers against which mineralization may "dam up" to form a deposit of economic interest A particular stratigraphical unit may, furthermore, act as a suitable host for replacement ore bodies.

The economic mineral potential of the greenstone belts now appears set for large-scale revision and revival of interest. Concentration has, in the past, centred mainly around economic gold mineralization, to the exclusion of base metal mineralization. This has resulted in little effort being directed at exploring for base metals, especially nickel, in the mafic and ultramafic rocks. It should become increasingly obvious that the greenstone belts must continue to be mineral exploration targets in the future.

F. THE WORLD-WIDE UNIFORMITY OF GREENSTONE BELTS

The characteristics of greenstone belts outlined so far can be found in all the known Precambrian shield areas of the world, and, apart from the well-known cratonic areas of Southern Africa (the Rhodesian and Kaapvaal cratons), well-documented accounts of greenstone belts from the Tanganyika (Tanzanian) craton in East Africa, the Western Australian shield, the Canadian shield, and the Indian shield are available. Although the Canadian shield has been the source of more research than most of the other shield areas the essential uniformity of the greenstone belts of its various provinces (Table 2) has been obscured by problems of stratigraphic correlation and nomenclature which seem to be more apparent than real. What cannot be denied is the existence of a group of predominantly volcanic rocks,

TABLE 2

TABLE SHOWING THE SUGGESTED LITHOSTRATIGRAPHIC CORRELATION OF GREENSTONE BELTS OF THE SHIELDS

GROUP	AFRICAN SHIELD			WESTERN AUSTRALIAN SHIELD		INDIAN SHIELD	CANADIAN SHIELD		
	South Africa	Rhodesia	East Africa	Yilgarn Block	Pilbara Block		Superior Province	Churchill Province	Slave Province
SEDIMENTARY GROUP	Moodies Fig Tree	Shamvian	Kavir-ondian	Yilgarn "Whitestone"	Mosquito Creek	Upper Dharwar	Timiskam-ing Knife Lake	Sickle Missi	Yellow-knife Group (B)
GREENSTONE GROUP	Onver-wacht	Bulawayan	Nyan-zian	Kalgoorlie "Green-stones"	Warra-woona	Middle and Lower Dharwar	Keewatin-Coutch-iching Abitibi-Pontiac?	Wasekwan Amisk	Yellow-knife Group (A)
ULTRAMAFIC GROUP	Onver-wacht	Sebakwian	?	?	?	?	?	?	?

overlain by a group of predominantly sedimentary rocks, in the greenstone belts of the Canadian shield, the whole being characterized by low-grade metamorphism and a particular tectonic style, whether it be in the Superior, Churchill, or Slave provinces. The stratigraphy, structure, metamorphism, relationship to shield granites, and, above all, the geotectonic setting, are common to all, with minor variations from belt to belt. It is noteworthy that the Ultramafic Group (Table 2) has only been fully recognized in Southern Africa, but metamorphic derivatives such as talc-tremolite and tremolite-chlorite schists have been reported from the Western Australian and Canadian shields, so that it is possible that this group is present outside Southern Africa, without its significance being recognized. On the other hand the Ultramafic Group may simply be absent from many greenstone belts. Stockwell (1957), Stockwell and Williams (1964), and Wilson (1965) have summarized the geology of the Canadian shield, and despite the seeming complexity of the early Precambrian, it is clear that the greenstone belts described from various parts of the shield have very strong similarities to each other. The problems of correlation over wide areas in such terrain will only be solved when each greenstone belt is taken in the context of early Precambrian shield geology and the large-scale geotectonic setting.

David (1950) has summarized data on the Western Australian shield, and his account is very similar in many respects to Macgregor's (1951) summing up of the early Precambrian geology of Rhodesia. Recent work by the Western Australian Survey (Noldart and Wyatt, 1961; Horwitz and Sofoulis, 1964; Ryan, 1964; Ryan and Kriewaldt, 1964) has emphasized the remarkable similarity of greenstone belts in both the Yilgarn and Pilbara Blocks and Ryan (1964) has suggested that the Archean rocks of the Pilbara Block represent a complete geosynclinal cycle. There is a strong northwesterly grain across the Western Australian shield, similar to the northeasterly grain across the shield remnants of Southern Africa, and this is considered to be a fundamental pattern, initiated across the continental crust before the deposition of the greenstone belts. The Dharwar System of the Indian shield (Wadia, 1957) appears to be closely similar to the early Precambrian sequence of the Rhodesian shield (Macgregor, 1951), and, again, its overall characteristics are closely analagous to the other ancient granite-greenstone areas of the world.

Perhaps, the first geologist to recognize the significance of the structural evolution of the Rhodesian greenstone belts was Maufe (in Maufe et al, 1919). His ideas were pursued to a logical conclusion by Shackleton (1946) in the latter's account of the Migori gold belt in the Tanganyika shield. Recent work by the authors' on the Barberton greenstone belt (Kaapvaal craton) and the Tati belt (Rhodesian craton) has resulted in the accumulation of data on the stratigraphy, structure, and metamorphism of parts of these belts (Anhaeusser et al, 1967; Viljoen and Viljoen, 1967; Mason, 1968). One of the few comprehensive accounts of the sequence and relationships of the granites of an early Precambrian shield is that by Hunter (1965), on the Swaziland granites; otherwise, the granites of these shields have yet to be investigated in any detail. However, it can be said that, in all the Precambrian shields, the various types of granites outlined previously in this account can be recognized. There appears to be a well-defined sequence of granites which have had variable influences on the evolution of the greenstone belts and the shields as a whole. At the present day, the shields are preserved as the most stable, the thickest, and the coolest parts of the earth's crust (Clark and Ringwood, 1964) and, further, they are all characterized by radiometric ages which place their initiation at pre-2900 million years. Younger ages may be identified where subsequent tectono-thermal events have affected the shields, and this is particularly well-displayed in the Canadian shield (Stockwell and Williams, 1964).

Mineralization in the greenstone belts has long been a subject of investigation, and the gold deposits of Canada, Western Australia, India, and various parts of Africa (excluding the Witwatersrand Sequence in South Africa) are all located in early Precambrian greenstone belts. The potential of the shield areas as base metal sources has not yet been fully realized, but the environment and geological conditions pertaining especially to late intrusive granitic rocks, which act as ore-concentrators, are very promising.

PRECAMBRIAN MOBILE BELTS

Surrounding and dividing the early Precambrian cratonic nucleii of the shield areas of Africa, a series of metamorphic mobile belts can be recognized, which are often superimposed across one another. Although not as well-defined in other shield areas, it is the authors' contention that similar belts probably exist in most shield areas. The Grenville belt in Canada, for example, appears to be very similar to some of the Southern African mobile belts. These mobile ("orogenic") belts have been regarded as a series of geosynclines which have undergone deep burial, orogenesis, and subsequent erosion, to reveal the root zones of the orogens, typified by high-grade regional metamorphism, accompanied by widespread granitization (Holmes, 1951 and 1965). Thus it has been contended that what is exposed today is the infrastructure, in which deformation was essentially related to flowage of mobilized material.

The concept of continental accretion stems from the above ideas which suggest progressive accretion of mobile belts onto stable cratonic nucleii. However, it has recently been pointed out that some of these mobile belts have incorporated cratonic remnants (Kennedy, 1964; Holmes, 1965; Cahen and Snelling, 1966), and that, in fact, the belts may represent geosynclines built on an existing continental floor. When the metasomatic transformations in these belts, reflected by widespread granitization, are considered, it is a logical inference to take the mobilized basement floor of these belts as the source of potassium and other granitizing fluids. To what extent the mobile belts constitute reworked cratonic material (granites and greenstone belts), as against reworked cratonic material with infolded supracrustal Proterozoic formations is as yet undetermined.

The mobile belts are essentially linear zones, containing high-grade, granitized, metamorphic tectonites which show evidence of rheid flow and reveal sporadic anatexis leading to masses of granitic rocks. Regional metamorphism, under amphibolite and granulite facies conditions, characterize the mobile belts, and it is noteworthy that sillimanite is the most widely developed of the aluminium silicate polymorphs in these belts. Kyanite is important in some belts, but andalusite, though not common, may also occur. Cordierite may be widely developed, and often occurs in granulite facies rocks with hypersthene. There are so many variables of composition and physico-chemical conditions of metamorphism in a mobile belt that many seemingly anomalous associations may be present. It is thus debatable whether any meaningful generalization as to metamorphic facies series (Myashiro, 1961) can be applied to the mobile belts. A great deal more detailed petrographic and chemical work is necessary before the mobile belts can be sensibly classified.

Very often, these belts are characterized by transcurrent dislocations, and there is usually evidence of repeated fault movement, both horizontal and vertical, along these dislocations. Furthermore, these mobile belts have acted as zones of crustal weakness since their inception, and evidence of mantle disturbance can be seen in volcanic activity of various ages and types, and in the emplacement of igneous ring complexes, which are often alkaline in character, together with kimberlites (Crockett and Mason, 1968). Thus, whatever the radiometric age of the latest tectono-thermal event recorded in a mobile belt, the belt will still remain a zone of instability with regard to faulting and igneous activity.

The structures typical of mobile belts are very different from those encountered in the greenstone belts and they reflect fundamental differences in the geotectonic setting of these two units. In the greenstone belts there is little, or no granitization, and the low-grade metamorphism is reflected in the fine structures, such as schistosity and crenulation cleavage, whereas the mobile belts are characterized by coarsely foliated, highly metamorphosed tectonites, which reflect the mobile, granitized environment. Complex folding in the mobile belts is often difficult to relate to a sensible regional stress system, and interference patterns produced at surface suggest several periods of refolding, involving isoclinal folds, and the development of dome and basin structures. The main mechanism behind the folding in the mobile belts is flow, and as Wynne-Edwards (1963, 1967) has pointed out, the production of complex fold patterns in a continuous sequence of deformation can be adequately and convincingly explained by flow folding. Lineation developed in these tectonites is usually related to mineral alignment parallel to rod and mullion structures, the whole being parallel to major fold axes. Another structural element encountered throughout the mobile belts is boudinage, and this is also intimately related to the folding.

A high proportion of the rocks occurring in the mobile belts are gneisses of various types, which are often regarded as metasedimentary. Unfortunately, the effects of granitization usually obscure the original features of these rocks, and, in any case, the refoliation of granodiorite or granite, and the regional metamorphism of dacitic and rhyolitic volcanic rocks, could equally well produce gneisses which are identical to those evolved from greywackes, shales, and arkoses. Apart from the gneisses, there are certain rock-types which appear in, and seem to be common to, all these mobile belts. These include amphibolites, marbles with associated calc-silicate rocks, and metaquartzites, often with associated magnetite quartzites. These rocks may represent infolded remnants of Proterozoic strata which were deposited on a depressed part of the early Precambrian crust, and which were subsequently sheared, heated, and mobilized, to form a mobile belt. It is unlikely that geosynclines, as such, developed on the sites of most of the Precambrian mobile belts. The amphibolites may represent metabasaltic volcanic rocks of a Proterozoic succession, or they may be syntectonic intrusive rocks, or a combination of both. These amphibolites should be distinguished from those derived from calcareous sedimentary rocks. A feature of the mobile belts are zones of cataclastic gneisses and mylonites, developed especially in parts which have suffered major transcurrent dislocation.

With regard to remnants of shield material in the mobile belts, it is noteworthy that parts of the Tanzanian craton have been traced into both the Mozambique belt and the Ubendian-Rusizian belt, and that the Zambezi, Limpopo, and Mozambique belts contain recognizable cratonic remnants (Holmes, 1951; Cahen and Snelling, 1966). The same type of evidence has appeared in the Grenville of Canada which contains cratonic remnants, together with supracrustal marbles and quartzites incorporated with the shield material (Wynne-Edwards et al, 1966). Just as the greenstone belts of the cratonic areas may be traced into mobile belts in many instances, it is to be expected that Proterozoic strata may be traced from cratonic areas where they may be unmetamorphosed, into the mobile belts where they become high-grade metamorphic tectonites.

One of the most striking and problematical features of the mobile belts is their uniformity of high-grade metamorphism, granitization, and structural style along linear zones of the crust. These reconstituted crustal strips are swamped with potassium which must have been derived from the early Precambrian granitic rocks, and provide excellent exampled of metasomatic transformation caused by potassium rising and spreading from the mobilized "basement". It is envisaged that streaming of volatiles from the mantle, in conjunction with high heat flow generated in the belt, reactivated potassium in the granitic basement during the mobile phase of its evolution. The structural style is governed by two factors, namely rheid flow and transcurrent dislocation, the latter resulting in cataclasis where the belt was no longer fully mobile. It is suggested that the flow patterns were controlled by confining cratonic nucleii, and that the sub-crustal agency which initiated transcurrent movement also produced the high heat flow from the mantle, which was necessary to mobilize the belt and start rheid flowage.

It has been suggested (H. Martin, personal communication, 1968) that a great thickness of Proterozoic sediments along the site of the mobile belt could preserve a zone of higher heat flow, and bring the belt in close proximity to a mantle heat source, following isostatic readjustment of the sedimentary pile, thus inducing metamorphism and granitization.

The Damaran belt, described by Martin (1965) and Clifford (1967), represents a thick pile of sedimentary rocks, with minor volcanic rocks accumulated on a gneissic basement. It does not appear to be typical of other mobile belts in Africa, in that parts of the belt are not metamorphosed, and there is a sporadic type of heating and mobilization instead of the uniform linear heating typical of most mobile belts. Furthermore, it is not certain to what extent transcurrent movement was involved in the evolution of the belt. However, the extensions of the Damaran belt in Zambia and Rhodesia are characterized by transcurrent dislocation (de Swardt, 1965), high-grade metamorphism, and granitization. The Damaran may be an intermediate stage in the formation of a typical mobile belt, but it may equally well represent a type of belt essentially different from the Mozambique and Limpopo belt-types.

Geochronology has revealed that mobile belts may be reactivated by superimposed tectono-thermal events at subsequent stages of the earth's history (Holmes, 1951; Cahen and Snelling, 1966). The discrepancies arising from dates of pegmatites, compared with whole-rock and biotite ages of the metamorphic tectonites, may be explained in terms of continuing mantle disturbance along these zones, which produced the pegmatites without actually reheating the whole belt again. The tendency to regard the latest tectono-thermal event in a mobile belt as the beginning of stabilization ignores the fact that these belts remained zones of instability in subsequent times, although it is recognized that the metamorphic mobility of the belt is subsequently restricted, or ceases altogether.

A major facet of the mobile belts is their economic potential. Such zones of mantle disturbance may give rise to base metal deposits, kimberlites, and rare metals, such as those associated with alkaline complexes. Furthermore, it is becoming more and more apparent that many of the major base metal deposits of Canada, Australia, and Africa are associated with Proterozoic rocks, the deposits being syngenetic in most cases. If it is assumed that Proterozoic supracrustal strata were incorporated with shield material in many of the mobile belts, then at least a certain amount of any base metal mineralization present in the Proterozoic strata would be preserved in the mobile belts after mobilization, having migrated into suitable lithological and structural environments. The mobile belts have too often been neglected in the search for economic mineral deposits, and their potential is only just beginning to emerge.

SUMMARY AND CONCLUSIONS

The early Precambrian greenstone belts evolved as discrete depositories on a relatively thin granitic crust, and were sited along fundamental crustal fractures, the grain of which can often still be recognized in many shield areas, and along which deep troughs appear to have developed at the initiation of the greenstone belts. Subsequently, their shape was modified by various episodes of granite intrusion, and the typical arcuation of the belts was produced. The calc-alkaline sequence of volcanic rocks is typical of the greenstone belts, and evidence of alkaline and spilitic volcanic associations appears to be lacking. An Ultramafic Group of lavas, with minor interbedded sedimentary rocks, chiefly of chemical origin, represents the initial phase of volcanic activity in a greenstone belt, but, so far, this group has only been fully recognized in Southern Africa. The Greenstone Group, consisting of basalts, andesites, dacites, and rhyolites, with interbedded clastic and chemical sedimentary rocks, usually dominates the stratigraphy of any greenstone belt, and this group represents a progressive sequence from mafic to salic volcanic rocks following the initial ultramafic phase. Unconformably overlying the preceding volcanic phases of any greenstone belt, rocks of the sedimentary group are usually to be found. These rocks represent the closing stages in the evolution of a greenstone depository, and, as such, are intimately related to the volcanic rocks. Here, unconformities are not important in the correlation of the greenstone belt, when the belt is taken as a complete cycle and entity. The subsequent deformation and metamorphism of each greenstone belt produced low-grade metamorphic tectonites, characterized by a steep linear schistosity and crenulation cleavages. It is postulated that the structure and metamorphism of any greenstone belt was a response of the belt to upwelling of granites, and the concomitant downsagging of the heavy pile of volcanics and sediments in the belt, and that the structures produced in these belts are a result of essentially vertical movements, with compression induced by the upwelling granites at high structural levels. The metamorphism along the contacts of the belts has been caused by heat from the granites, but the proximity of the belt to mantle heat sources, because of the relatively thin crust, and the frictional heat generated during deformation may also have been important. Whatever the heat source, the metamorphism was low-grade, and in belts preserved from subsequent tectono-thermal events there is a complete lack of any granitization phenomena.

A strongly contrasted geological evolution is envisaged for the Precambrian mobile belts which are essentially high-grade metamorphic gneiss belts characterized by complex fold and fault structures and granitization. It is suggested that most mobile belts represent reworked cratonic material, with or without infolded supracrustal Proterozoic rocks, and that the initiation of these belts was triggered by huge transcurrent dislocation and a high heat flow related to mantle sources. The granitization of these belts is explained by potassium metasomatism, with the reworked granitic shield rocks as the source of potassium and other volatile elements. Many of the complex fold structures appear to be related to non-uniform laminar flow during a stage of rheidity in the belt.

The volcanic and sedimentary processes which can be identified in the greenstone belts, together with the geochemical separation of iron, silica, alumina, titanium, barium, calcium, etc. in them, suggests that these early Precambrian depositories were not quite as primitive as some authors have intimated (Macgregor, 1951; Pettijohn, 1943, etc.). The distinctive and probably unique factor which can be associated with the greenstone belts is their geotectonic setting and their formation on a crust, the nature of which has never subsequently been simulated because of progressive thickening during continental evolution since early Precambrian times. In this respect uniformitarianism cannot be upheld, but many of the volcanic, sedimentary, metamorphic, and structural features of the greenstone belts have been reproduced separately, in various environments, throughout subsequent geological time.

The mobile belts have been visualized as the exposed "roots of mountain chains", or the "infrastructure of orogenic belts", and theories stemming from the geosyncline concept, and Alpine tectonics, have been applied to these belts in an effort to explain their geology. If the mobile belts incorporate cratonic granite-greenstone terrain, then geosynclinal theory cannot be applied to them with any realism, and there is little evidence that Alpine tectonics were involved in the evolution of these belts. In fact, in the environment of the mobile belts, flowage phenomena are to be expected, and it thus becomes necessary to find a convincing mechanism for the initiation of flowage. Why the mobile belts developed over certain parts of the Precambrian shields and not over others, could be related to crustal fracture patterns which evolved as a result of some system of mantle disturbance. This unsatisfactory conclusion can only be made more satisfactory when a new approach to Precambrian shield geology is made, and more facts on fracture patterns are made available by workers from the various Precambrian shields.

Concepts of Precambrian geology based on theories evolved from Alpine geology appear to be misleading, and, as more work is done, these concepts seem to have less and less relevance to the problems of Precambrian geology. A new approach to the geology of early Precambrian greenstone belts, the granitic terrain which surrounds them, and to the mobile belts is advocated. It is suggested that the structure and metamorphism of the rocks involved will only be elucidated and fully understood when concepts such as "regional compression", "depth of burial" related to metamorphism and granitization, and Alpine tectonics are either more critically appraised, or discarded altogether. The economic implications of a better understanding of the Precambrian shields and mobile belts are considerable since it is becoming more and more obvious that these features control, or are directly related to, many of the world's economic mineral deposits.

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