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GREENSTONE BELTS: THEIR COMPONENTS AND STRUCTURE.

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Although in common geological usage there is considerable ambiguity over the definition of greenstone belts which are historically regarded as long and narrow in shape, Archaean in age and composed of volcanic and sedimentary sequences at greenschist facies. This definition remains true for many of what are commonly regarded as greenstone belts but others differ significantly, particularly in shape and metamorphic facies. For this reason the term 'succession' is prefered for greenstones which are not particularly linear. In the following discussion it is our intention to maintain 'greenstone' as a useful term and for that reason we specifically aim to exclude high-grade supracrustal gneiss terrains such as those of the central zone of the Limpopo belt and early Precambrian supracrustal sequences such as the 3Ga Pongola, the 2.7Ga Witwatersrand and the 2.4Ga Ventersdorp from any definition of greenstone successions. We also aim to include all commonly accepted greenstone successions. The following points are of relevance to the definition of greenstone belts:

1. Most commonly accepted greenstone successions are of Archaean age but a few younger belts have been reported from Wisconsin, USA (1) and northern Quebec, Canada (2).
2. Although many greenstone successions are long, linear and narrow (e.g. Pietersburg and Murchison, Kaapvaal craton) many others have more irregular shapes (eg. Bulawayan, Zimbabwean craton and Pilbara, Western Australia). The word 'belt' therefore is inappropriate for some greenstone successions.
3. Volcanic rocks are ubiquitous components whereas sediments may be of secondary importance. The volcanics frequently include komatiitic rocks. Intrusive igneous rock units such as layered complexes, dykes and sills may be present.
4. Greenstone successions occur at metamorphic conditions from sub-greenschist to granulite facies and the colour prefix, refering to the greenschist facies, is unfortunate.
5. Deformation intensity within the greenstone successions is variable.
6. Greenstone successions are always intimately associated with and surrounded by trondhjemite-tonalite-granodiorite-granite granitoids.

We tentatively suggest the following definition:

Greenstone successions are the non-granitoid component of granitoid-greenstone terrains. Volcanic rocks are an essential component, some of which are usually komatiitic. Sedimentary rocks are commonly present and igneous intrusive units may exist. The greenstone successions are linear to irregular in shape and where linear they are termed belts. The greenstone successions may occur at all metamorphic facies and are heterogenously

deformed. Most greenstone successions are Archaean in age.

Greenstone successions comprise a wide variety of rocks, dominated by volcanics, which are usually altered and deformed. Alteration of volcanic and other rock types is manifested by hydration with variable silicification (3), carbonate-isation (4) or silica loss (5) as well as isochemical metamorphism. Alteration itself is temporally and spatially variable, Smith and Erlank (6) have described possible early sea floor alteration of komatiitic rocks from Barberton and carbonate-isation in Murchison is patchy and syn- to post-tectonic. This alteration constrains identification of original rock-types and the use of whole rock chemistry. This restriction added to the problems of equating area of surface outcrop with rock volume means that estimates of greenstone lithological proportions must be treated circumspectly. However, greenstone successions commonly comprise the following primary lithologies: komatiitic, mafic and felsic volcanics, cherts, banded iron formations, shales, graywackes and quartz arenites. Less commonly limestones (including stromatolites), arkose, ultramafic and mafic layered complexes, quartz-feldspar porphyries and quartz tholeiite dykes are present.

The identification of the environment of emplacement of greenstone igneous rocks is highly problematic. Subvolcanic intrusions exhibit many features almost indistinguishable from true lavas. Skeletal crystal growths, commonly grouped under the all-embracing term of 'spinifex', are an important textural form in these rocks and these textures, in abundance, are restricted to Archaean greenstone successions. These textures are indicative of rapid crystal growth under supersaturated conditions (7) and need not be restricted to lava flows. In fact, the inordinatly thick cumulate zones associated with some spinifex-bearing rock-types preclude these being lava flows in the currently accepted sense and the non-genetic term 'cooling unit' has been used to describe these layered rocks which may represent lava flows or subvolcanic intrusions. The recognition of crescumulate type crystal growth and rhythmically developed spinifex units indicate a variety and complexity of mechanisms which have given rise to these textures and criteria should be established to permit the environment of emplacement to be determined more precisely. Symmetry of structures and spinifex textures encountered in some units may be indicative of dyke emplacement.

Until recently, greenstone research was largely oriented towards deducing a unifying model, subsequently heterogeneity has become the key-word. In essence, greenstone belts are of different ages and formed in different tectonic situations. Groves and Batt (8) recognise both younger and older greenstone successions in Western Australia in two distinct environments, determined on the basis of volcanic constituents, sedimentary facies, mineral deposits and tectonic style, to which they gave a genetic interpretation as rift-phase or platform-phase greenstones. Whereas this is a major development in understanding Australian greenstones the division of other greenstone successions into rift- and platform-phase is tenuous, particularly for those of the Kaapvaal craton. The Murchison greenstone belt, for instance, has characteristics of both rift- and platform-phase greenstones.

The Barberton greenstone belt, comprising the lower komatiitic to felsic units of the Onverwacht Group and overlying deep water sediments of the Fig Tree Group, probably represents a rift-phase (8) and the overlying Moodies Group with shallow water quartzites and banded iron formation is typical of a platform-phase greenstone belt. However, herewithin lies an important observation on greenstone successions: the environment of formation can vary within a greenstone. This variation may be due to either:

1. A progressive evolution in environment. (Eriksson (9) has described the Fig Tree to Moodies group evolution of the Barberton greenstone belt in terms of an evolving back-arc, or passive continental margin.)
2. The superposition of different environments which are temporally separate and manifested in the field by an unconformity.

or 3. Some or all of the units are allochthonous and represent spatially and/or temporally diverse environments now tectonically juxtaposed.

Another aspect of the heterogeneity is the recognition of both continental and oceanic environments. The Mberengwa greenstone belt of Zimbabwe rests unconformably on granitic rocks (10, 11, 12). Basement has also been inferred to exist beneath other greenstone belts in Australia, Canada and India (13, 14, 15). Major layered igneous complexes such as Dore Lake (16) and the Rooiwater, Murchison greenstone belt (17), are a significant component of some greenstone belts. These complexes have minor ultramafic components, anorthosite-gabbro layers, magnetitite layers and a highly differentiated and sodic granite. These complexes are analogous to bodies such as the Bushveld and are intrusions in a continental environment.

In contrast to the continental environment of some greenstone successions no proven continental basement exists at the base of the Barberton greenstone belt and the Onverwacht Group may be partially of oceanic origin (18). In addition, some ultramafic complexes may also be ophiolitic (19). De Wit and Stern (20) have recognised a possible sheeted-dyke complex in the Onverwacht group. Support for the obducted oceanic origin for some greenstone rocks comes from the recognition of podiform alpine-type chromites at Shurugwi (Zimbabwe) (21, 22) and at Lemoenfontein (Kaapvaal craton) (23). These have textural and chemical characteristics similar to those recognised in ophiolitic complexes of Phanerozoic age.

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Historically greenstone structures were regarded as simple synformal belts between sub-circular rimming granitoid domes. This relationship has given rise to genetic interpretations that greenstone belts are pinched-in synformal keels between domal or diapiric granitoids or between granitoid domes which are the result of interference folding (24). Unfortunately the paucity of detailed structural observations and accurately determined stratigraphic successions mean that few of the assumed synforms are proven.

In the Kaapvaal craton the Murchison, Pietersburg, Sutherland, Rhenosterkoppies, Amalia and Muldersdrift belts lack a gross synformal structure. At Barberton the greenstone succession comprises several synformal structures separated by steep reverse faults (25). De Wit (26) and Lamb (27) have recently described thrusts, some of which emplace Onverwacht volcanics over Moodies sediments. The suggestion of Anhaeusser (28) that deformation structures within the Barberton greenstone belt can mostly be related to granitic diapirism is at variance with the observed thrust structures and evidence presented by Ramsay (25), Roering (29) and Burke et al. (30) who note deformation structures prior to granite intrusion, intrusive granite contacts oblique to deformation structures and an absence of deformation structures within the greenstone directly related to those in the surrounding granitoids.

We suggest that whereas broadly synformal belts may exist this is not a characteristic of greenstone belts. Many of the intrusive granitoids are undoubtedly domal but intervening greenstone belts are not necessarily synformal and the role of diapirism in controlling the structure of greenstone successions may be over-emphasised.

In deducing the overall large-scale structural characteristics of greenstone successions the following general observations may be relevant:

1. Contacts with the surrounding granitoids can be either tectonic (31) or intrusive with dykes and veins of granitic rock in the greenstone belts and a static high T/low P metamorphism near the greenstone contact with the granitoids suggesting contact metamorphism by igneous intrusion.
2. Geophysical evidence from a number of belts suggests they are shallow with vertical depth extents rarely more than 10km and usually less than 5km (32, 33), figures considerably less than the proposed stratigraphic thicknesses of these belts. This shallow depth extent suggests no simple rotation of the usually upright greenstone belt but instead a truncation which may be a major decollement zone, recumbent syntectonic granite or a late intrusive contact.
3. Recumbent fold structures and possible thrusts are relatively common and have been described from greenstone successions of the Zimbabwean craton (34, 35), of the Kaapvaal craton (25, 26, 27),

of the Western Australia shield (36, 37) and the north American shield (38).
4. Greenstone successions occur as either linear belts or as irregular shaped units comprising arcuate arms.
5. Late-deformation structures and the present disposition of primary layering structures in the greenstone successions are usually upright.

Greenstone successions are composed of deformed and metamorphosed (including metasomatised) rocks. However despite the obvious difficulties, many authors have proposed stratigraphies for greenstone belts, but some have deduced total stratigraphic thicknesses dramatically in excess of those predicted by currently accepted models for basin formation (39, 40). Greenstone successions such as Barberton with 17 to 23km (41), Pietersburg with 21.4km (41) and Abitibi with over 30km (42) or up to 45km (43) total stratigraphic thickness contrast with both thinner sequences from other greenstone and non-greenstone early Precambrian supracrustal sequences such as the Witwatersrand. It is the greenstone successions with large stratigraphic thicknesses which are invariably at sub-greenschist or greenschist facies and without the high grades of metamorphism that would be expected at the base of these sequences. These thicknesses represent one of the challenging problems in greenstone geology.

Possible explanations for the large stratigraphic thicknesses are as follows:
1. They are an artifact of combining separate sections into a composite section or are oblique sections.
2. That incorporated within the greenstone belt and incorrectly interpreted as part of the stratigraphy are layered igneous complexes, sills and tectonically rotated dykes.
3. The stratigraphic sequences are in fact related to two or more spatially superimposed but temporally separate and essentially unrelated events. In the Barberton greenstone belt granite cobbles in a Moodies Group conglomerate have yielded zircons giving ages of 3.15Ga (44) contrasting with ages of 3.54Ga (45) for the stratigraphically lower Onverwacht volcanic rocks. A major phase of granite emplacement separates these two dates and a major unconformity may exist at the base of the Moodies Group.
4. They are not true stratigraphic sections but are structurally repeated by imbricate thrusting and/or folding. To achieve significant structural repetition by thrusting, folding or both requires major recumbent tectonics on or above a decollement plane.

Whilst explaining large stratigraphic repetition the recumbent thrust-fold model also predicts metamorphic conditions at the base of the pile initially at high P/low T and with thermal relaxation to medium pressure facies. Bickle et al. (46) have reported such rocks from the Yilgarn and similar staurolitekyanite-bearing rocks occur in the Murchison greenstone belt. However the very large apparent stratigraphic thicknesses with associated sub-greenschist or greenschist metamorphism remain unexplained by horizontal thrust-nappe tectonics. These may however be explained by repetition above a flat decollement in an imbricate stack with associated folding. In this situation the stratigraphy is turned on end and multiply repeated but the structure remains shallow. Zones of cyclic repetition should be investigated to determine if the cyclicity is real or the result of imbricate stacking. Examples of this type of structural stacking resulting in repetition are provided by Coward et al. (35) from Matsitama, Zimbabwean craton, Botswana and Martyn (37) from the Kalgoorlie area in the Norseman-Wiluna greenstone belt (Western Australia).

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