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THE ROCK COMPONENTS AND STRUCTURES OF ARCHEAN GREENSTONE BELTS:
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Much of our understanding of the character and evolution of the earth's early crust derives from studies of the rocks and structures in Archean greenstone belts. Our ability to resolve the petrologic, sedimentological, and structural histories of greenstone belts, however, hinges first on an ability to apply the concepts and procedures of classical stratigraphy. Unfortunately, early Precambrian greenstone terranes present particular problems to stratigraphic analysis, some of which we would like to discuss here. We would also argue that many of the current controversies of greenstone belt petrogenesis, sedimentology, tectonics, and evolution arise more from our inability to develop a clear stratigraphic picture of the belts than from ambiguities in its interpretation.

We will here consider four particular stratigraphic problems that afflict studies of Archean greenstone belts: (a) determination of facing directions, (b) correlation of lithologic units, (c) identification of primary lithologies, and (d) discrimination of stratigraphic versus structural contacts.

(a) Facing Directions: Determination of facing directions in greenstone belt sequences is often difficult because of the absence of useful facing indicators throughout great thicknesses of section and because we do not sufficiently understand the origins of many structures and textures in Archean sedimentary rock types to be able to use them as facing indicators. Thick sequences of massive volcanic rocks, banded black and white cherts, black cherts, and banded iron formation are inevitably rather stingy in yielding familiar facing indicators whereas thick turbiditic units, layers of graded accretionary lapilli, and sands containing large-scale cross-stratification are particularly user-friendly in this regard. Facing directions in banded cherty units are most readily determined from fluid escape features, particularly pockets of druzy quartz, which originate as pockets of trapped fluid, usually directly beneath early-lithified white chert bands. Geopetal accumulations of debris in cavities, cracks, and at the bases of early-formed breccias and the preferential development of stalactitic dripstone in stratiform cavities (the development of both stalactitic and stalagmitic dripstone is also common, but stalagmites alone are extremely rare) are also widespread and useful as facing indicators in cherty successions. In all cases where supporting evidence is available in adjacent sedimentary units, we have found pillow geometry and drain-out cavities, where developed, to be reliable facing indicators in tholeiites.

Small-scale cross-laminations, load structures, and individual graded detrital layers must be approached with caution because nearly identical features can form facing upward or downward. Pillows, where present in komatiitic sequences, generally lack useful facing information. The recent trend to quantify the reliability of facing estimates (e.g. 95% confidence) is misleading inasmuch as the principal errors in determining facing directions originate not through statistical ambiguities in the structures themselves but from their misidentification by the investigator.

(b) Correlation: The correlation of stratigraphic units within poorly exposed, structurally complex, highly altered Archean terranes represents a major challenge to unravelling greenstone belt stratigraphy and evolution. The absence of useful guide fossils and the paucity of unique, recognizable

time markers, such as distinctive ash beds, makes this task difficult relative to similar studies in Phanerozoic terranes. Recent precise zircon age dating in the Canadian belts is aiding in resolving gross problems of stratigraphy, but will do little for detailed correlation.

In the early Archean Barberton and Pilbara belts, we have found a number of features particularly useful in correlation: (1) lithologically and texturally distinctive layers of airfall and/or turbiditic accretionary lapilli, (2) individual airfall ash beds in sequences of orthochemical and biogenic deposits, (3) airfall spherule layers, (4) distinctive sequences of non-facies controlled deposits, and (5) rare, facies-related units and sequences. Least reliable are distinctive successions of environmentally or petrogenetically controlled lithologies that can be repeated many times within individual sections as sedimentary environments and magmatic systems come and go. Even continuous, traceable lithologic units cannot serve as unambiguous time markers unless there is independent evidence that they are not diachronous.

(c) Primary Lithologies: Perhaps as much as any other problem, our inability to decipher primary lithologies has hampered the development of a clear picture of greenstone belt make-up and evolution. It has long been recognized that early alteration is pervasive throughout greenstone belts. This alteration was for many years considered part of the post-accumulation metamorphic history of these belts. More recently, however, the trend has been to attribute alteration to relatively high-temperature exhalative to shallow-subsurface hydrothermal processes (1, 2) or to low-temperature metasomatism, perhaps related to the circulation of surficial waters through the rock sequences (3).

Interpretation of the primary MgO contents and petrogenesis of komatiites, role of calc-alkaline and subduction-related volcanism, presence or absence of volcanic cycles, distribution of felsic lavas, nature of metamorphism and metasomatism, provenance of detrital sediments, composition of early surface waters, and sedimentology of cherty units have all been stymied to some extent by uncertainties in the composition of the original sedimentary and volcanic layers. A number of relatively recent studies have shown clearly that (i) many specific units previously interpreted to be silicic volcanic rocks are actually silicified mafic to ultramafic lavas (e.g. 2, 3), (ii) many of the "classic" mafic-to-felsic volcanic cycles are non-existent (4) although large-scale volcanic cyclicity seems to be widely developed (5), (iii) calc-alkaline volcanics, as well as komatiites, are abundant in some belts but poorly represented in others, (iv) some belts exhibit a more-or-less continuous spectrum of rock compositions from komatiitic to rhyolitic whereas others are strongly bimodal or trimodal; (v) evaporitic sediments, especially gypsum, were widespread and abundant constituents of shallow-water Archean greenstone-belt sedimentary deposits (6), (vi) relatively few, if any, cherty layers represent primary silica precipitates (7), and (vii) there may be important lithologic and tectonic differences between early and late Archean greenstone belts (7).

Many of the remaining ambiguities in the alteration histories of these rocks originate because most studies of alteration are focused on identifying the role or evaluating the influence of one particular style or setting of alteration. Clearly, some silicification and carbonatization began concurrently with deposition and involved essentially surface waters at surface temperatures. The abundance of cherts in shallow-water sequences but their paucity in deeper-water units (7) suggests that early post-

depositional fluctuations in water chemistry (e.g. deposition in marine but early flushing by meteoric waters) may have been an important control on silicification. Later large-scale recrystallization and replacement almost certainly occurred both through low-temperature processes, similar to those affecting modern oceanic crust, as well as during local higher-temperature, hydrothermal and black-smoker-type metasomatism and mineralization. The widespread presence of epidote and resetting of isotopic systems, such as Ar-Ar, clearly argue for still later regional metamorphism, and the localization of silicification along some joints and fractures indicates continued alteration under fully post-tectonic and post-metamorphic conditions. Future studies must provide unambiguous criteria for distinguishing stages and environments in this prolonged alteration history, many of which may leave similar mineralogical and textural records.

(d) Stratigraphic vs. Structural Contacts: Greenstone belt sequences are characteristically highly deformed, typically showing polyphase deformation and structural repetition through faulting and folding. One of the principal problems facing structural, stratigraphic, and tectonic synthesis of greenstone belts lies in distinguishing between structural and stratigraphic contacts in areas of poor exposure and in the near-absence of unambiguous tools for relative age determination and correlation. Whereas it was once fashionable to regard thick, apparently intact, uniformly facing successions of volcanic and sedimentary rocks in greenstone belts as forming coherent stratigraphic sections, often in excess of 15 km in thickness, the present tendency is often to infer that such sequences, at least on this planet, are composite, formed by the tectonic repetition of considerably thinner stratigraphic sections.

The problem, now as previously, is the field recognition of faults, particularly stratiform faults, such as thrusts. In the Barberton belt, for instance, there are large areas, particularly in upper parts of the succession, within which nearly stratiform thrust faults are present and can be easily recognized using conventional means: (1) truncated and offset stratigraphic units and folds, (2) unambiguously repeated stratigraphic sequences, (3) the development of mylonitic and brecciated zones along fault planes, and (4) the formation of drag folds in units adjacent to the faults. However, throughout most of the classic sections of the Onverwacht Group in the southern part of the belt, major faults identifiable by such conventional criteria are absent. Although it has been suggested that most of the apparent 12-km thickness of the Komati, Hoogenoeg, and Kromberg Formations is an artifact of isoclinal folding of a much thinner sequence (2), studies of facing directions throughout the section do not bear out this interpretation (3). Arguments have also been advanced (2, DeWit, this meeting) that chrome-mica-bearing alteration zones at the tops of komatiitic units within this sequence represent stratiform shear zones with displacements of perhaps 1-10 km. Unfortunately, however, these units display none of the usual characteristics of faults (such as cross-cutting relationships) and are developed only at the tops of komatiitic flows (never at the tops of tholeiitic or felsic units). They exhibit cataclasis and schistosity only where cross-cut by clearly later, through-going faults or where present in areas where all units show penetrative deformation. In most sections, these rocks display well-preserved, unsheared primary spinifex and cumulate textures. Inferences that these zones represent faults must at some point be based on a systematic consideration of their characteristics, including clear enumeration of features indicating an

origin through faulting and the means of determining displacement.

Although it is clear that our ability to unambiguously differentiate structural and stratigraphic contacts in greenstone belts without fossils or rather fortuitous combinations of features will remain limited, the use of conventional criteria cannot be abandoned entirely. The possibility that thick, stratigraphically intact sequences are present in greenstone belts must remain as a working hypothesis until internal faults or folds can be identified based on clearly defined and well-understood criteria.

As noted above, it is our assessment that much of the controversy surrounding greenstone belt tectonics and evolution originates not from ambiguities in the genesis of rocks and structures in greenstone belts but from ambiguities in what those rocks and structures are and were. Future resolution of these controversies will rest more on careful, systematic studies of individual aspects of greenstone belts than on broad-brush syntheses or non-systematic collections of observations. A clear example of the success of the systematic approach is the role detailed geochronological studies have played in resolving the evolution of the late Archean Canadian belts. These studies (e.g. 5) have confirmed the existence of large-scale volcanic cycles within the Canadian greenstone belts and the existence of stratigraphic sections up to 10 km thick.

The results of any attempted overview of the similarities and differences among Archean greenstone belts depend significantly on how the term "greenstone belt" is defined. Presently used definitions (8) range from exceedingly broad (supracrustal successions in which mafic volcanic rocks are predominant) to relatively narrow (those requiring specific components, such as ultramafic or komatiitic lavas, and the increasingly common, largely implicit definition equating greenstone belts and ophiolites). Based on consideration of features common to most of the greenstone belts discussed in the present set of abstracts, we offer the following definition:

Greenstone belt - an orogen made up largely of mafic to ultramafic volcanic rocks and their pyroclastic equivalents and epiclastic derivatives, showing intense macroscale deformation but regionally low grades of thermal alteration, and extensively intruded by penecontemporaneous or slightly younger granitoid plutons.

Virtually all terranes commonly considered as greenstone belts are encompassed by this definition, including many Phanerozoic examples. A critical aspect of this definition, and one that requires careful consideration, is that the terms "greenstone belt" and "ophiolite" are not synonymous. Rather, as in Phanerozoic orogens, ophiolites or ophiolite-like sequences may be components of greenstone belts.

Even with the restrictions imposed by this or most other definitions, greenstone belts constitute a highly diverse family of terranes. Some include an essentially continuous spectrum of komatiitic, tholeiitic, and calc-alkaline lavas, such as many belts in the Superior Province; others show a strongly bimodal volcanic suite (Barberton). Some are dominated by eruptive rocks (Superior Province, eastern Pilbara Block, and Barberton), others by sedimentary units (Slave Province and many Indian belts). The volcanic sequences in older greenstone belts (Barberton and eastern Pilbara) accumulated under shallow-water, anorogenic platform conditions; those in

most younger belts represent deep-water, tectonically active settings (7). Additional differences have been noted by other investigators (9, 10). These differences encompass nearly as much variability as represented by the spectrum of modern orogens. A possible implication of this diversity is that greenstone belts may represent tectonic settings as varied as those represented by modern orogenic belts.

The results of most modern studies of greenstone belts suggest that close scrutiny of individual belts usually allows identification of lithologically and structurally analogous modern terranes and, by inference, tectonic settings. There is an emerging consensus, for instance, that the petrologic, structural, and geochronological characteristics of large parts of the Superior Province indicate that it is an assembly of late Archean volcanic arcs formed along convergent plate boundaries that were basically similar to volcanic arcs and convergent boundaries today (Card, this volume). An important dissenting view, however, is expressed by David and others (this volume). Parts or all of the volcanic sequences of other Archean belts have been interpreted to represent oceanic or simatic crust formed at spreading centers.

Using a similar argument, the more-or-less regular vertical stratigraphic succession in greenstone belts, including lower volcanic and upper sedimentary stages, is grossly similar to the stratigraphic sequences in many modern orogens. If a genetic similarity is indicated, then it may be expected that individual greenstone belts include rocks formed in an evolutionary spectrum of tectonic settings. Perhaps, under ideal conditions of preservation, these may range from cratonic rift and/or ocean floor settings near the base to volcanic arc and, in some instances, cratonic or peri-cratonic settings at the top.

At the same time, if we look closely at individual greenstone belts, many features can be identified that are not present in their younger analogs. These include the common presence of extensive komatiitic lavas, banded iron formation, ocean-crust-like sequences (ophiolites) in excess of 10 km thick, and regionally extensive shallow-water sedimentary units deposited in anorogenic simatic settings. Some of these features, such as banded iron formation, reflect differences in modern and Archean systems that are probably unrelated to tectonics. Others, such as unusually thick ocean-crust sequences and widespread shallow water simatic platforms, may reflect important differences between Archean and Phanerozoic tectonic systems, if not in fundamental character then in local expression.

Future resolution of many of the outstanding controversies of greenstone belt evolution rests in detailed systematic studies of (i) individual properties of individual greenstone belts (structural style, alteration, sedimentology, petrology), (ii) differences among Archean greenstone belts, and (iii) similarities and differences between Archean belts and younger, apparently analogous terranes.

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