every available place. The population of organisms may not have been diverse, but it would have been as dense as the sunlight, chemical supplies, and lack of predators allowed.

Finally, from the sedimentological record a reasonable, though not conclusive, case can now be made for the proposal that the atmosphere has been at least weakly oxidizing for most of the geological record. Sulphate evaporites in 3.6 Ga greenstones in the Pilbara and Barberton (Lowe and Byerly), and Nondweni (Hunter *et al.*, described at the workshop) lend some support to this notion.

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A Petrologic Viewpoint

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Instead of attempting to summarize what you all heard during the past two days, I will build on some of the topics and issues discussed to outline an approach to understanding the progressive development of continental crust in the Archean greenstone belts.

What interests petrologists is the relationship between the observed magmatic rocks, the inferred source rocks from which magmas are derived, and the processes inbetween. The possible processes are numerous, and they obscure the links between product and source. The processes are physical, and it is the physics of solid-melt-vapor systems that controls the chemistry of the magmas, and of the igneous rocks perserved in the geological record.

Using the Barberton Mountain Land as an example, the most prominent igneous rocks in early Archean terranes include (1) komatiites, (2) tholeiites, (3) tonalites and trondhjemites, grey gneisses, (4) potassic granites, pink gneisses, and (5) rare syenites. In some Archean terranes monzodiorites and syenites appear to correspond to the igneous stage represented generally by the grey tonalite and trondhjemite gneisses. Dacites and rhyolites may be abundant, presumably the surface expression of large magma chambers.

The possible source rocks are: (1) peridotite and eclogite of the mantle, (2) komatiites and tholeiites of the protocrust, possibly hydrated with formation of serpentine, talc, chlorite, epidote, and amphibole, (3) locally, garnet-amphibolite or amphibole-eclogite from oceanic crust thickened, foundered, or subducted, (4) tonalite gneiss of new continental crust, and (5) metamorphosed sediments buried by compressive tectonics, or subduction.

These observed magmatic products and inferred sources for the Archean are found in petrographic associations throughout geological history. The materials are the same, although additional materials become more important in post-Archean times. The one distinctive feature of the Archean is the existence of abundant komatiites, and this feature alone is sufficient to inform us that the asthenosphere was, at least locally, hotter by several hundred degrees than in later history. Two of the problems in komatiite petrogenesis are (1) attaining high enough temperatures, and (2) retaining the liquid at depth with its host peridotite for the relatively high percentage of melting required to generate the low-viscosity, high-MgO liquids. Because the thermal structure at depth is so fundamental for igneous processes, I maintain that the komatiites merit another round of detailed investigation, starting in the field, with petrography, mineralogy, and geochemistry; and with a major effort to strip off the effects of obvious and more subtle alteration, with experimental petrology of komatiites and peridotites to provide the calibration for the geophysical and thermal modelling.

More vigorous convection of the mantle in the Archean would probably be concentrated in plumes, and the existence of komatiites suggests that temperatures in these plumes may have been at least a couple of hundred degrees higher than in later regions of upwelling. The idea that pools of komatiite magma could be formed in the mantle in regions of local upwelling is very attractive, and its geophysical and petrological implications merit more attention. There is now persuasive, although not definitive, evidence that the density of komatiite liquids becomes higher than that of peridotite at a depth of 200–300 km. If so, komatiite magma formed at greater depths could not rise through this level and would in contrast have a tendency to sink. The conditions for intermittent release of komatiite from mantle magma chambers are speculative, but the tectonic conditions must involve tension. The reports of sheeted dikes in the Archean are probably more important as indicators of tension than as indicators of the possible presence of ophiolites that could be similar to modern oceanic crust.

MAGMAS \ SOURCES	PER.	ECLO.	Hb-GAB.	TONAL.	GRANITE
KOMATIITE	√	X	X	X	X
BASALT	√	X	X	X	X
TONALITE	√ H_2O < 40 km	X	√ HIGH T	X	X
TRONDHJEMITE	X	X	√ H_2O	√	X
GRANITE	X	X	X	√ H_2O	√
SYENITE	X	X	X	X	√ H_2O > 50 km

Fig. 3. Archean magmas: Possible and impossible sources. Based on major elements, mineralogy, and phase relations. Trace element and isotope geochemistry must also be considered.

If komatiites were derived from deep magma chambers, then the tholeiites can be interpreted as having been formed from a different source, lithospheric mantle at a shallower level, with heat provided by the deeper mantle plumes.

There is evidence for the storage of magmas of different composition in chambers at different depths. Calderas and associated volcanic activity confirm the presence of shallow silicic magma chambers. The widespread distribution of large anorthite crysts in many basaltic rocks is strong evidence for large, long-duration basaltic magma chambers at greater depths. In addition, large komatiite magma chambers may have existed in the upper mantle. There has even been discussion of a magma ocean, capped by lithosphere, but I prefer a picture with the chambers localized in regions of strong mantle upwelling.

Evidence from experimental petrology denies the prospect of deriving primary granitic magmas from normal mantle peridotite, and geochemical signatures leading to this conclusion must be satisfied by partial melting of young material derivative from mantle, such as basic rocks or greywackes. Tonalites and trondhjemites are derived not from the mantle, but from basic protocrust. For these magmas, we need additional experimental phase equilibrium data to define the ranges of pressure, temperature, and water content for their derivation. The structures of rocks in greenstone belts, leading to inferences about tectonic environment and process, need to be interpreted in terms of possible depths of formation and emplacement, for correlation with the experimental phase equilibrium data on the magmas. The coordination of these two approaches should lead to a clearer understanding of whether the granitoid magmas are formed as a result of crustal thickening, sinking of blocks of the crust, or an early version of subduction (presumably on smaller scales).

The general approach of using experimental petrology to unravel possible relationships between the observed magmatic rocks and the inferred source rocks is to follow the geochemists in "forward" and "inverse" approaches, and to use the phase diagrams to place major element constraints on the magic of minor element and isotope algebra. This approach neglects the very influential "processes" between source and near-surface products, but it provides a framework for starting to unravel the petrogenesis.

In the forward approach, the possible source rocks are subjected in the laboratory to variation in P, T, H_2O content and other variables, which provides specific information about the compositions of melts and coexisting minerals generated in the rocks under any conditions investigated. This sounds easy, but there are many experimental difficulties.

In the inverse approach, the near-liquidus phase relationships of an igneous product are determined through a range of P, T, and other variables such as H_2O content; the minerals on the liquidus of the particular composition must then correspond (in type and composition) to the residual minerals in a possible source rock at the specified conditions of pressure, temperature, water content, or other defined variables.

Much effort has been expended in these two approaches for peridotite-basalt, and less for peridotite-komatiite. Incomplete data are available for combinations of the series gabbro-tonalite-trondhjemite-granite-H_2O. On the basis of the available data, Fig. 3 is offered as a matrix of possible and impossible magmas from possible sources in the Archean. I have assumed that in the Archean, deep subduction of cool oceanic lithosphere does not occur. I adopt the idea of a basic protocrust generated where tension permits uprise of magmas from mantle sources, followed by the formation of mini-continents, their migration and collision, with foundering of parts of the colliding continental nuclei, and local shallow subduction into an upper mantle hotter than it is today.

The sequence of igneous products in the Barberton Mountain Land, komatiites and basalt, tonalites and trondhjemites, granites, and finally syenites, also constitute possible magmatic sources. The sequential development of each magmatic product by partial fusion of the preceding igneous phase is consistent with major element phase relations. This interpretation appears to fit the physical conditions reasonably well, and appears to be reconcilable with much trace element and isotope geochemistry. Refinement of the structural geology and correlation with phase equilibrium results of experimental petrology might lead to a better definition of the extent of vertical movements in the Archean, and with the temperatures at various depths associated with these structural movements.

WORKSHOP ON

TECTONIC EVOLUTION OF GREENSTONE BELTS

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