THE NATURE OF THE UPPER MANTLE AND LOWER CRUST

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GEOPHYSICAL, TECTONIC AND GOECHEMICAL FRAMEWORK

The major layering of the crust and upper mantle has been largely defined by the discontinuities (Moho, 670km discontinuity, Conrad discontinuity, low velocity zone) revealed by studies of seismic wave velocities. The concept of plate tectonics has enforced a major distinction between a relatively rigid lithosphere (containing the Moho) and an underlying convective asthenosphere. The age and nature of the modern oceanic lithisphere is moderately well constrained by considerations of sea-floor spreading, plate tectonics and obducted slabs of ocean floor. In contrast the construction and origin of the continental lithosphere (crust and mantle), which has evolved through a much longer period of time, remains the complex puzzle which has long excited the deliberations of geoscientists.

Recently, extensive data from seismic reflection experiments have revealed that the lower continental crust is frequently characterised by many, often sub-horizontal, reflectors. Such reflectors occur beneath Archaean and tectonically-young terranes (Smithson, 1986), and there is considerable uncertainty concerning their origin or origins (?small-scale lithological layering, mylonite zones, H_2O-rich layers). Layering of the lower crust by basic intrusions may be an extensive cause of the reflectors and increases speculation concerning the widespread occurrence of underplating. Dipping seismic reflectors in the upper crust often die out in the lower crust, but some (e.g. the Outer Isles Thrust of north-west Scotland) may continue and displace the Moho. Most recently the occurrence of strong reflectors (both dipping and sub-horizontal) has been identified in the upper mantle lithosphere (McGeary and Warner, 1985).

In order to explain the origin of many features of the stable continental lithosphere, it is natural to turn to the processes seen in presently active tectonic regimes. But in endeavouring to interpret features of the continental lower crust and mantle lithosphere, it is often difficult to assess whether extensional or compressive tectonic regimes have had the major influence. Thus basalt injection during rifting, and tectonic imbrication and mylonite formation during continental collision, may both be invoked to explain lower crustal seismic reflectors. Similarly, major aspects of layering of continental lithosphere may be attributed to subduction zone processes (Oxburgh and Parmentier, 1978), whilst recent seismic reflection data from the Basin and Range province (USA) suggest that the Moho is related to Cenozoic magmatism and extension (Klemperer et al., 1986). In general a polygenetic origin of features in the continental lower crust and mantle lithosphere must be expected (Fountain and Salisbury, 1981; Smithson, 1986).

Within cratons, the above uncertainties are compounded by lack of knowledge concerning global tectonic processes in the Archaean. With the prominent exception of komatiite distribution, there is little evidence from exposed Archaean terranes of the higher-than-present-day geothermal gradients which might be expected from abundances of radioactive elements.

Geophysical and geochemical evidence may be adduced to support the concept of layered mantle convection, with the upper convecting layer extending to a depth of about 700km (Richter and McKenzie, 1981). This upper convecting layer may be equated with the asthenospheric reservoir of MORB, which (with its depleted trace element and isotope characteristics) may be broadly viewed as the long term compliment to the differentiated continental crust. In addition to the MORB reservoir (asthenosphere), other potential reservoirs with distinct geochemical signatures are: the lower mantle, continental crust, continental mantle lithosphere, oceanic crust and oceanic mantle lithosphere. In explaining the geochemistry of different basalt provinces (oceanic islands, continental alkali basalts, continental flood basalts, arc volcanics) these different reservoirs are tapped to varying degrees by different authors (e.g. Allegre et al., 1983; Hofmann and White, 1982; McKenzie and O'Nions, 1983). The physical position of these reservoirs is not fixed; thus oceanic lithosphere may be partly incorporated in continental lithosphere and recycled to the asthenosphere, whilst continental lithosphere may also return to the asthensphere. However, the geochemical constraints provided by the identification of these (or other) reservoirs, provides a framework, which can interact with observations on xenolith types in different provinces, to develop an understanding of both upper mantle constitution and basalt genesis (Hawkesworth et al., 1983).

XENOLITHS AND THE NATURE OF THE LOWER CONTINENTAL CRUST AND MOHO

Xenoliths believed to represent the lower continental crust and Moho region are available from igneous rocks erupted in a wide variety of tectonic environments (e.g. convergent plate boundaries, intraplate rifts, stable platforms and cratons) - Kay and Kay (1980). In general the xenoliths reveal dominantly basic lithologies but with widely variable proportions of ultrabasic and metasedimentary rocks.

The basic rocks range from pyroxene-plagioclase rocks, which in some cases may represent little-metamorphosed igneous cumulates, to thoroughly-metamorphic amphibolites, garnet pyroxenites and eclogites (e.g. Wass and Irving, 1976; Griffin et al., 1979; Upton et al. 1984). When xenoliths from one locality are assembled (by a combination of P-T estimates and wishful thinking) into vertical sections, an interdigitation of basic and ultrabasic rocks across the crust-mantle boundary may be indicated (Griffin et al., 1984; Jackson, 1980). The occurrence of garnet-pyroxene-granulites in the uppermost mantle can be argued if P-T estimates are considered in isolation.

The ages of initial formation of many xenoliths attributed to the lower continental crust are evidently old (e.g. Rogers and Hawkesworth, 1982). However, there is uncertainty concerning the age of the metamorphic mineral assemblages in xenoliths by comparison with their age of eruption; and evidence exists in some cases of metamorphism considerably before eruption (Harte et al., 1981). If P-T estimates from a suite of lower crustal xenoliths all refer to the same time then they may be used to construct fossil geotherms. As might be anticipated such geotherms often indicate relatively high heat flow regimes; again, whether these geotherms pertain to the time of eruption or some preceding compressional or extensional tectonic regime is a moot point. Evidently more data on the ages of these xenoliths and their mineral assemblages is much needed.

XENOLITHS/XENOCRYSTS AND THE NATURE OF THE CONTINENTAL MANTLE LITHOSPHERE

The majority of xenoliths are peridotites, pyroxenites and eclogites. Often the pyroxenites seem to be genetically related to peridotites, but the associations of the eclogites (and also grospydites) are less clear. The formation of eclogites from subducted oceanic lithosphere has been suggested (Helmstaedt and Schulze, 1979). The peridotite xenoliths from basaltic hosts are usually non-garnetiferous, whilst those from kimberlitic hosts are garnetiferous; but exceptions occur. Within both spinel-peridotites and garnet-peridotites evidence of initial ages of formation of 1 to 3.5 Ga may be found (e.g. Cohen et al., 1984; Menzies et al., 1985). Recent data from diamond inclusions (Richardson et al., 1984) not only yield evidence of >3 Ga old continental lithosphere, but of geothermal gradients at that time which were similar to those of present-day shields.

Considering the peridotite xenoliths and their relationships the following points may be noted:-

(1) A large proportion of the common coarse or protogranular xenoliths are depleted in basalt constituents. However many of these xenoliths show a secondary LREE enrichment, which may often be relatively recent (e.g. Menzies et al., 1985).

(2) Garnet-peridotite xenoliths from kimberlite pipes are often of two major types: coarse peridotites with low estimated temperatures (<1100°C) of equilibration

and deformed peridotites with high estimated temperatures of equilibration. The cold coarse group are often highly depleted in basaltic constituents, whilst the hot deformed group are usually more fertile and may have trace element and isotope signatures indicative of the MORB asthenosphere reservoir (Richardson et al., 1985). It is debated whether the hot deformed peridotites have 'primary' compositions (Boyd and Nixon, 1975), or secondary compositions caused by interaction with an 'asthenospheric' magma, whose presence is also shown by Cr-poor megacryst suites (Harte, 1983).

(3) In southern Africa the cratonic region mapped at the surface, finds expression in the mantle lithosphere mapped at depth by the distribution of diamonds, low-calcium garnets and the equilibration conditions of high-temperature peridotites (Boyd and Gurney, 1986).

(4) A wide variety of peridotite-pyroxenite xenoliths showing modal metasomatism are found. In many cases this metasomatism appears to be consequent upon the incursion of melts. Several associations of metasomatic nodules and eruptive rocks may be broadly recognised: (a) alkali clinopyroxenite nodules from highly alkaline continental volcanics; (b) kaersutite/pargasite and mica bearing nodules from alkali basalts; (c) ilmenite-rutile-phologopite-sulphide nodules from kimberlites; (d) richterite and mica bearing nodules from kimberlites. The enriched trace element inventories of such nodules and the longevity of the continental mantle lithosphere endorse it as a potentially important goechemical reservoir.

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