PETROLOGIC CONSTRAINTS ON GEOPHYSICAL MODELS FOR THE LOWER CRUST, MOHO AND MANTLE: THERMAL AND SEISMIC INTERPRETATIONS

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INTRODUCTION

Studies of the deep crust and uppermost mantle require the integration of petrologic and geophysical data to produce a geologically realistic model. Geophysicists need to incorporate into their modelling the petrologic constraints which are now available in considerable detail. The actual rock types present at depth, their relative proportions and stratigraphic relationships can be inferred from studies of xenolith suites and exposed terranes of tectonically-emplaced deep-seated sequences. Conversely, petrologic models must be consistent with the geophysical data including both field measurements (eg. seismic results) and laboratory measurements on the physical properties of the real rock types.

XENOLITH DATA AND GEOTHERMS

Xenolith-bearing basaltic and kimberlitic rocks are widespread on the earth's surface and hence give a statistically reasonable geographical sampling of the deep-seated rock types from all tectonic environments. We believe that the following traditional beliefs about the nature of the lower crust, Moho and upper mantle are challenged by the xenolith information. Geophysical models generally assume that the lower crust is andesitic, relatively homogeneous and that its thermal state can be described by a "continental geotherm". The Moho is commonly considered to be a sharp boundary both seismically and petrologically and to represent a discrete rock-type change from granulites to ultramafic rocks, this change being marked by an increase in compressional wave velocity (Vp) to about 8 km/sec. The upper mantle is generally modelled as homogeneous peridotite with Vp > about 8 km/sec.

Xenolith suites reveal that the granulite- and eclogite- facies xenoliths which represent lower continental crustal material are overwhelmingly mafic (including plagioclase-rich types such as anorthositic) compositions (Griffin and O'Reilly, 1986a, 1986b, 1987). There are subordinate amounts of felsic meta-igneous rocks and very rare metasediments. Eclogite-facies rocks from the lower crust are restricted to some cratonic areas. Tectonically more active regions (e.g. eastern Australia) are characterized by granulite-facies lower crust, high geotherms and gradients in seismic velocity across broad (10-30 km) crust-mantle transition zones. P/T estimates on xenoliths, and exposed crustal sections, suggest that such gradients are due to interlayering of mafic rocks with felsic granulites in the lower crust, and with spinel lherzolite in the uppermost mantle.

A xenolith-derived geotherm for present-day southeastern Australia was constructed by O'Reilly and Griffin (1985) using geothermobarometry calculations on well-equilibrated mineral assemblages in xenoliths (mainly garnet websterites) from two young maars in western Victoria. P and T data from xenoliths from other basaltic provinces of various ages were then shown to plot on this geotherm. This geotherm gives a much higher T at any P than conventional continental or even oceanic geotherms. It has a strong curvature from about 10-30kb, indicating significant advective transfer of heat in the lower crust and upper mantle consistent with intrusions of basaltic magmas in those regions. This contrasts with the steady-state model conductive geotherm which has a shallower curvature at low pressures due to the assumption of simple conductive heat loss. This geotherm is higher than that of cratons (e.g. Western Australia). These differences in thermal state of contrasting continental lithosphere types are crucial in the interpretation of seismic data, especially when the lower crust is mafic.

MODEL FOR THE CRUST/MANTLE BOUNDARY

Using all the available xenolith information for eastern Australia it is possible to construct a lower crust/upper mantle stratigraphy that is consistent with petrologic, P/T and geophysical data (Fig. 1). The crust/mantle boundary (CMB) occurs at about 25km which is the depth where ultramafic rocks (spinel lherzolites) start, and increase in proportion with depth. The black horizontal lines represent layers of mafic rocks which are frozen basaltic liquids or their cumulates (which may or may not have re-equiblirated to granulite or eclogite facies conditions). These decrease in proportion both up and down from the CMB. All lower crustal wall rocks are mafic to felsic granulites. The layers of mafic rocks represent repetitive basaltic under- and over-plating at the CMB by intrusive and tectonic processes.

Reversed seismic profiles for eastern Australia (Finlayson et al., 1979) show that there is a gradient in Vp from about 25 km to 55 km where Vp = approx. 8 km/sec (Fig. 1) and thus represents the seismic Moho. 55 km is the predicted depth where the southeastern Australian geotherm crosses the spinel to garnet lherzolite boundary (Griffin et al., 1984). Therefore it is suggested that in continental regions of high geothermal gradient, the seismic Moho represents the transition from spinel- to garnet- lherzolite rather then the CMB which represents the change from granulite to lherzolite wall rock.

Calculated (O'Reilly and Griffin, 1985) and measured (Bezant, 1985) Vp's for real mantle rock types are consistent with this interpretation. These Vp values for spinel lherzolites are less than 8 km/sec for two main reasons: (i) the higher geothermal gradient lowers Vp and (ii) real mantle-derived spinel lherzolites generally contain significant (>40% pyroxene) which gives a lower Vp than peridotite which is usually used as the upper mantle rock type for modelling.

In order to address this problem, Bezant (1985) has devised a method for realistic estimation of Vp at 10 kb and 25°C for mafic and ultramafic rocks with different modes. Figure 2 illustrates the results for an olivine/clinopyroxene/orthopyroxene assemblage. This is based on the correlation of measured values of Vp (for three mantle-derived lherzolites) with those calculated using single crystal data (also based on laboratory measurements) for various modes. A temperature correction must be used for these values (e.g. Christensen, 1974) from T's derived by geothermometry calculations for the given mineral assemblage.

Another feature of seismic information are the zones with abundant horizontal reflectors (which we interpret as the mafic lenses) observed at depths of 15-35 km in many parts of the continental crust. These zones are usually described as "lower crust", with the seismically transparent zone below being "mantle". Despite demonstrations that the refraction Moho coincides with the base of such zones, this does not require that either the Moho, or the base of the layered zone, corresponds to the CMB. Where the uppermost mantle contains numerous subhorizontal lenses of mafic rocks (Fig. 1), this will appear as a layered zone on reflection profiles and will have a bulk density and Vp intermediate between "crust" and "mantle" values. Thus the "refraction Moho" and the "reflection Moho" must coincide in such areas, even though part of the layered zone would be regarded as "mantle" in the petrographic sense.

EFFECT OF GEOTHERMAL PROFILES ON SEISMIC INTERPRETATION

Figure 1 represents a lithospheric model for eastern Australia which is consistent with seismic evidence. In contrast, cratonic areas such as Western Australia usually show a shallower, sharper Moho. Such differences have been interpreted as due to contrasting types and thicknesses of crust. However, an important difference is the lower geothermal gradient of cratons. For mafic rocks, different thermal profiles are critical in determining whether or not the equilibrium mineral assemblage lies in the eclogite or the granulite facies, and hence in determining the Vp of these deep-seated regions.

The formation of the crust-mantle transition by magmatic under- and over-plating will inevitably be accompanied by an elevated, strongly curved geotherm like that for southeastern Australia. When the magmatic activity ceases, this geotherm will decay towards a conductive geotherm, like the Western Australian one, with a time constant on the order of 10 Ma.

With successive cooling, mafic assemblages convert from granulites to eclogites

With successive cooling, mafic assemblages convert from granulites to eclogites at shallower depths (Griffin and O'Reilly, 1987). This transition to eclogite results in an increase in Vp of 0.5 to 1.0 km/sec. The decrease in T will also raise the Vp of the other rock types, resulting in a maximum increase in Vp near the CMB. In terms of geophysical interpretation, the seismic Moho moves upward and becomes much more pronounced as a result of the cooling.

Useful petrological interpretation of geophysical data (especially seismic reflection and refraction surveys) requires knowledge of the local geothermal profile and of the effect of T on the stability of mineral assemblages at depth. The location of the CMB and its nature are critical to the solution of large-scale geological problems such as the nature of the evolution of the mantle, and mechanisms of crustal formation and growth throughout Earth's history. Neither petrologists nor geophysicists should allow considerations of these fundamental issues to become clouded and restricted by semantics such as traditional interpretations of the significance of terms like "Moho".

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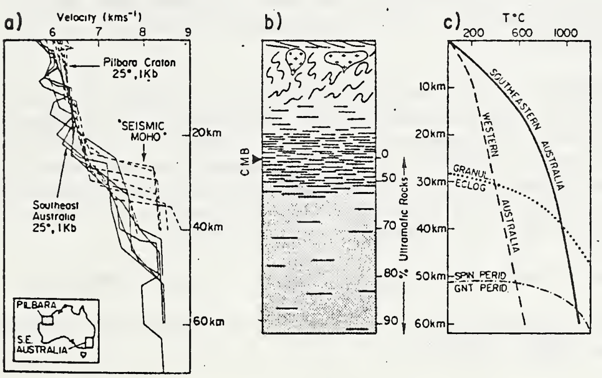

Fig. 1a: Vp profiles for southeastern Australia and the western Australian craton.

b: Petrologic model for the crust/mantle boundary (CMB) in non-cratonic regions.

c: Geotherms for southeastern Australia (xenolith-derived) and western Australia (extrapolated from heat flow).

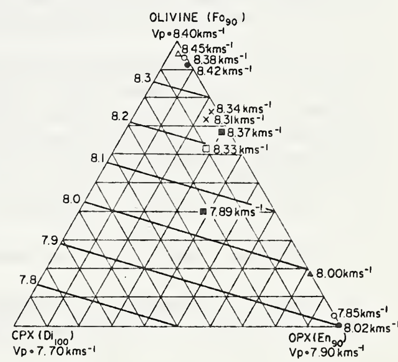

Fig. 2. Graphical estimation of Vp for oliv/opx/cpx modes at 25°C and 10 kb.