4-D LITHOSPHERE MAPPING: CONSTRUCTING STRATIGRAPHIC SECTIONS OF THE LOWER CRUST AND UPPER MANTLE IN SPACE AND TIME

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4-D lithosphere mapping is a methodology, based on the use of xenoliths and mineral concentrates from basaltic, kimberlitic and similar volcanics, that draws together geophysical, petrological, geochemical, tectonic and geochronological information to construct geologically realistic sections showing the detailed nature of the deep crust, lithospheric mantle, the crust/mantle boundary (CMB) and the asthenosphere/lithosphere boundary. The *geophysical data* provide remotely-sensed and broad-scale information on the physical responses of mantle and lower crustal materials and define large-scale domains with contrasting properties. The *petrological data* provide more specific information on real rock types and their distribution with depth at specific localities. The petrological data constrain the interpretation of geophysical data: the geophysical information allows lateral extrapolation between the individual lithospheric stratigraphic columns constructed from xenoliths and mineral concentrates. Repeated volcanic episodes that have occurred in the same crustal region can be used trace thermal, physical and chemical modifications of lithosphere through time. Ancient lithosphere rejuvenated by fluid infiltration (metasomatism) may source younger volcanism in response to a new thermal pulse as old cratonic keels erode and transform.

Paleogeotherms derived from xenoliths or mineral concentrates for specific localities provide the essential reference framework for interpreting the structure of lithospheric sections (eg O'Reilly, 1993; O'Reilly and Griffin, 1995). They are a direct measurement of the thermal state of the lithosphere at the time of eruption of the host volcanic. Considerable information on deep processes is contained in the shape and position in P-T space of specific geotherms, especially by comparison with theoretical steady-state conductive model geotherms. Indeed the "real" shape of these model geotherms is imperfectly understood and even the most quoted versions of Pollack and Chapman (1977) have been defined using assumptions unconstrained by petrological information. This focus on geotherms as the basis for "4-D Lithospheric Mapping" also reflects the paramount role of thermal energy and thermal anomalies in Earth processes including the evolution of the crust and mantle. The (paleo-) geotherm at specific localities is used to place individual samples in their original stratigraphic position, and to give the distribution with depth of rock types and (with geochemical data) of processes such as metasomatism. These data can be combined with geophysical surveys to provide a 3-dimensional picture of the composition, structure and thermal state of the lower crust and upper mantle

The continental lithosphere includes the continental crust and the relatively rigid part of the underlying upper mantle, characterised by conductive heat transport. Considerable evidence suggests that the crust and the lithospheric mantle are two parts of a closely linked system, and that the nature of this system has changed markedly through geologic time. For example, some types of mantle-derived lavas (eg komatiites) erupted only at the early stages of the Earth's history, and have not contributed to crustal formation since then. Studies of mantle-derived xenoliths and minerals in volcanic rocks (eg Griffin et al, 1995)) indicate major differences in the thickness, composition and thermal structure of the upper mantle beneath continental provinces of different crustal age and seismic response (Boyd and Mertzman, 1987; Jordan, 1988). Some mantle lithologies, such as depleted garnet harzburgites, are restricted to areas with Archaean crust (eg Schulze, 1995), and the available data show major differences in the chemical composition of the mantle beneath terranes of different ages (eg Griffin and O'Reilly, unpubl. data). Seismic tomography (eg Jordan, 1988; Helmstaedt and Gurney, 1995) has shown that thick lithospheric keels also are restricted to the continental nuclei, mostly of Archaean age. These relationships are not accidental, but appear to reflect secular changes in the processes that produce lithospheric mantle.

Dating of mantle rocks and minerals (eg Zhao and McCulloch, 1993; Chen et al., 1994) strongly suggests that the formation/modification of lithospheric mantle and that of the overlying crust are complementary processes, and that in many regions the mantle lithosphere remains attached to that crust for aeons, until replaced or removed during tectonic episodes. But mantle roots also can be modified and eroded. In areas as diverse as eastern Brazil, Colorado/Wyoming and eastern China, ancient lithosphere has been removed and replaced by thinner, hotter and more fertile mantle during both rifting or collision events (eg Eggler et al., 1988). This lithosphere erosion changes both the heat budget and the composition of the subcontinental mantle, and those changes also control the style and composition of subsequent magmatism and associated mineralisation in the crust. Recognising regions where the crust and the underlying mantle have become decoupled is economically important, because such areas may become less prospective for some commodities (such as diamonds) but significantly more prospective for other commodities related to the subsequent magmatism (such as copper, molybdenum and gold).

Geophysics and Mantle Samples: Most of our information on the nature of the subcontinental lithospheric mantle is derived either indirectly, through large-scale geophysical studies, or directly from mantle xenoliths carried up in kimberlites and other volcanic rocks. The geophysical data provide the only realistic means of mapping large-scale variations in mantle structure and using this information to interpret major tectonic processes. However, the geophysics can only be interpreted realistically if information is available on the rocks present at depth in the study area, or in other areas thought to have comparable lithospheric geology. That information can in principle be provided by xenoliths where available and by garnet ± chromite mineral concentrates which have a wider spatial and temporal distribution.

The development of in-situ trace-element analysis by the proton microprobe, and its application to the heavy-mineral concentrates (HMCs) generated by diamond exploration programs, have greatly expanded the information potentially accessible on mantle lithology, geochemistry and thermal structure (Griffin and Ryan, 1995). For example, garnet grains in equilibrium with olivine can yield a temperature based on Ni content and a minimum pressure estimate (P_{Cr}). Similarly, temperatures can be derived from the zinc content of individual chromite grains. Analysis of 30-50 garnets and chromites from one locality can yield an estimate of the local paleogeotherm (Ryan et al., 1995), and the true depth of origin of each grain can then be estimated by reference of T_{Ni} and T_{Zn} to that geotherm. The geochemical information for each grain can thus be placed in stratigraphic context.

The original lithology from which each grain was derived can be interpreted by comparison of garnet and chromite compositions with those known from xenoliths, in which the paragenetic associations are apparent. Similarly, the geochemical signatures of a limited range of rock-forming processes have been recognised by study of xenoliths and the mineral inclusions in diamonds. Processes identifiable in the trace-element signatures of garnets and chromites include depletion by melt extraction, high-T melt-related metasomatism (Smith et al., 1993) and a lower-T process associated with the introduction of phlogopite (Shee et al., 1993).

Mantle Sections and Geophysical Interpretation: The compilation of all this information provides a stratigraphic section of the mantle under each locality which shows the vertical distribution of some rock types, the thermal structure, the depth to a (chemically defined) lithosphere base, and the distribution of depleted and metasomatically-enriched rocks. These sections can be compared with geophysical data to interpret specific features of the geophysics; for instance, the position of the lithosphere base inferred beneath Siberia (Griffin et al, this volume) correlates well with the Lehman discontinuity derived from Russian Deep Seismic Sounding experiments across this area. The position of the geotherm, which can be derived from the HMC data, is known to affect both density and seismic velocities (Morgan, 1995). The deep high-Vp roots seen in seismic tomography images of some cratons are widely interpreted as reflecting low temperatures at depth. However, these "roots" also may reflect the higher proportion of harzburgite relative to lherzolite in Archaean lithosphere, because the higher seismic velocities could be caused by this higher MgO content, rather than simply a lower T. With this kind of knowledge, the geophysical data can be interpreted more precisely, and then used to map the regional variation in specific lithologic/geologic parameters, between the sites where xenolith/heavy-mineral data are available. Different types of mantle lithosphere can be recognised, and tectonic boundaries, reflected in different ages and types of mantle, can be mapped and interpreted.

Mantle Domains: The determination of the size and nature of intraplate mantle domains is of fundamental importance in understanding the mechanisms and processes of mantle/crust evolution. Distinct regions of mantle can be mapped using trace-element and isotopic characteristics of whole-rock xenoliths and separated minerals mainly clinopyroxenes and garnets and the compositions of basaltic melts (eg, Menzies, 1990; Wilson and Downes, 1991; O'Reilly and Zhang, 1995). Available data indicate that the size, shape and geochemical characteristics of these mantle domains vary with respect to depth in the lithospheric column, with tectonic environment (eg craton, Phanerozoic fold belt, collision margin) and geographically for similar tectonic settings (eg., western Australia, southern Africa and Siberia cratons). Furthermore, large-scale mantle "events" inferred from geochemical and chronological (Nd-Sr isotopic and zircon ion-probing) methods indicate coupling with crustal tectonic episodes (eg O'Reilly and Griffin, 1988; Chen, et al, 1994). Differences in lithospheric type are also delineated by seismic, gravity and heat flow data (eg., Morgan and Gosnold, 1989) and MAGSAT imagery (Mayhew et al.,1985). Global distinction of cratonic and non-cratonic regimes has many important applications, such as understanding the distribution of diamond-bearing kimberlites.

4-D lithosphere mapping is a powerful tool in defining areas where diamonds may have been preserved or destroyed throughout Earth's geological evolution and in predicting target areas for new exploration.

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