The recognition of ultrahigh-pressure (UHP) minerals such as diamond and coesite in crustal rocks was a major breakthrough in Earth dynamics; it showed that subduction of the crust to >100 km depth occurs in continental-collision belts. In the Western Gneiss Region (WGR) of Norway, for example, continental subduction during the Caledonian Orogeny converted crustal rocks to eclogites over a 250 × 75 km area. The recognition of relict majoritic garnets (garnet-pyroxene solid solutions by Van Roermund and Drury (1998) in garnet peridotites extended that subduction to ≥150 km depth, and Scambelluri et al. (2007, p. 59 in this issue) have now pushed the WGR crustal slab to ~200 km.

Majorite—Evolution of an Idea


The first terrestrial majorite solid solutions were found as inclusions in diamonds from South African kimberlites. Tsai et al. (1979) reported two diamond-inclusion garnets with 3.10 and 3.28 Si from the Jagersfontein pipe, but did not note their significance. Their compositions indicate that the garnets formed in eclogite, the high-P equivalent of basalt. Moore and Gurney (1985) described eclogitic garnets with 3.15–3.43 Si in diamonds from the Monastery kimberlite and estimated pressures up to ≥14.6 GPa using the data of Akaogi and Akimoto (1977, 1979).

Since then, majoritic diamond inclusions have been reported from other kimberlites worldwide (Stachel, 2001). Most such garnets are eclogitic; about six are peridotitic. Diamond-inclusion majoritic garnets generally have high Na and Ti, due to substitutions such as Na+ + Si4+ = M2+ + Al3+ and Na+ + Ti4+ = M2+ + Al3+. Nearly all are homogeneous phases; exsolution of pyroxene or TiO2 at lower P was hindered by confinement in the enclosing diamond.

The next advance was the recognition by Haggerty and Sautter (1990) that some garnet-clinopyroxenite xenoliths from Jagersfontein contain broken-down majorite. Diagnostic microstructures include exsolved pyroxene ± rutile parallel to <111> in the cores of garnets with inclusion-poor rims, and decoration of garnet grain boundaries by small pyroxene grains. The reconstructed garnets have ~3.24 Si; this raises the possibility that the rock itself originally was a single phase. The whole-rock analysis can be calculated as a garnet with 49% majorite, similar to a diamond inclusion from Jagersfontein (Deines et al., 1991; Fig. 1), the most extensive natural solid solution known.

The first majoritic garnet from an outcrop was reported by Van Roermund and Drury (1998), who found exsolved pyroxene, rutile, and other phases in large garnets in a peridotite on the island of Otøy in the WGR. Re-integration of the exsolved pyroxene yielded an original (M1) garnet with 3%–7% majorite, and a later (M2) recrystallized garnet with 1%–2%. They suggested that the peridotites originally crystallized at depths >185 km (M1), and rose to ~150 km before cooling to allow further exsolution (M2). Spengler et al. (2006) described garnetites from Otøy with reconstructed majorite contents up to 20%, suggesting much greater initial depths. Garnets with 0.5%–1% majorite have been described in garnet peridotites from the Dabie-Sulu (China; Ye et al., 2000) and Qaidam (Tibet; Song et al., 2004) UHP belts, and from garnet pyroxene xenoliths in alkali basalts on Hawaii (Keshav and Sen, 2001).

Majorite contents can be converted to depth estimates by comparison with experimental data (Fig. 1). However, most experiments are at T = 1200 °C, and higher T produces greater solid solution. The calibration line in Figure 1 therefore probably gives maximum depths for deep-mantle samples, but minimum values for samples from continental-subduction zones, where T is <1200 °C (cf. Figure 1 of Scambelluri et al., 2007). Furthermore, the experimental data cover a limited range of bulk compositions; there remains “an urgent need for more studies on the variation of majoritic garnet compositions with P and T” (Van Roermund et al., 2001, p. 122).

This calibration (Fig. 1) suggests that most diamond-inclusion majorities are derived from depths of 250–350 km, but some may come from at least 400–500 km. This is consistent with the coexistence of majorite and silicate perovskites in some Brazilian diamonds (e.g., Kaminsky et al., 2001; Stachel, 2001). The Jagersfontein xenoliths may record the rise of a mantle diapir from ~300 km to ~400 km, whereas the Norwegian examples (M1-M2) suggest a rise from ~350 km to ~150 km.
in Archean time (Spengler et al., 2006). The third generation of majorite (M3; Scambelluri et al., 2007) suggests that the crustal slab carried the peridotites down again to depths of ~200 km, similar to the highest values estimated from mineral equilibria in garnet peridotites from the WGR (e.g., Brueckner et al., 2002; Lapen et al., 2007).

Anomalous Rutile—An “Early Warning” Observation?

Most majoritic garnets have high Ti contents, and rutile ± ilmenite exsolve along with pyroxene. Rutile is tetragonal, and should show extinction parallel to its elongation in crossed-polarized light. However, rutile needles with anomalous extinction (elongated parallel to an unidentified crystallographic direction) occur in the garnet and pyroxene of some eclogites from kimerlites and the WGR (Griffin et al., 1971), and in majoritic garnets from the WGR and the North Qaidam UHP belt (Van Roermund et al., 2000; Song et al., 2004). A possible explanation is that rutile originally exsolved as the orthorhombic \( \alpha - \text{PbO}_2 \)-structured TiO\(_2\) phase, which has been found in garnet from UHP gneisses of the Erzgebirge; if so, it could indicate \( P \geq 6 \text{ GPa} \) (Hwang et al., 2000). Anomalous rutile may be unreported but widespread in UHP rocks, and could serve as a tip-off that the garnets had majoritic precursors.

The Wider Context

The current explosion of work on continental UHP belts reflects their relevance to the dynamics of continental collision, subduction, and exhumation. These belts also can help us understand the formation and evolution of the subcontinental lithospheric mantle (SCLM), a highly contentious subject (e.g., Griffin and O’Reilly, 2007). Current models for UHP belts regard most of the peridotites as pieces of the SCLM from beneath the upper plate, picked up by the subducting crust at shallow to very great depths (Brueckner 1998; Brueckner and Medaris, 2000). These large mantle samples are spatially and temporally limited, and may be tectonically complex, but they are an invaluable adjunct to studies of xenoliths in volcanic rocks, where relationships between rock types are seldom obvious.

The majorites also raise questions about deeper mantle dynamics. How do samples from nearly 500 km depth arrive at the surface? Many of the diamond-inclusion majorites occur in kimerlites where other diamonds contain the ferropericlase + CaSiO\(_3\)-perovskite + MgSiO\(_3\)-perovskite assemblage that is stable in the lower mantle, even deeper than the majorites. These “super-deep diamonds” may have been transported in plumes (e.g., Griffin et al., 1999) (or kimerlites?; Haggerty, 1994) coming from the lower mantle. However, the multistage breakdown of the majorites in the WGR peridotites, and perhaps in the Jagersfontein xenoliths (Fig. 1) suggests that convection or diapirism may move volumes of solid mantle upward by hundreds of kilometers at a time. This type of convection may have helped produce the Archean SCLM, as suggested by Spengler et al. (2006)—perhaps a model for other areas as well?

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