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A tale of two orogens: the contrasting T-P-t history and geochemical evolution of mantle in high- and ultrahigh-pressure metamorphic terranes of the Norwegian Caledonides and the Czech Variscides

by *Hannes K. Brueckner*[1] and *L. Gordon Medaris, Jr.*[2]

Abstract

Garnet peridotite (GP) massifs within collisional orogenic belts provide windows into deeper levels of the mantle (100 to possibly > 400 km) than do spinel peridotites. A geochemical, isotopic and petrological study of GP from high- and ultrahigh-pressure metamorphic terranes in the Western Gneiss Region, Norwegian Caledonides, and the Gföhl Nappe, Bohemian Massif, Czech Variscides, suggest that more than one type of mantle can be involved in continent-continent collision.

GP from the Western Gneiss Region are chemically depleted, give consistent LT-HP estimates of garnet equilibration, and define old (Pre-Caledonian) Sm–Nd mineral crystallization and recrystallization ages. These ages match similarly old ages in the associated crust, implying that the mantle and crust were coupled. The Norwegian peridotites apparently sat in a cold, static mantle environment for a long time before they were incorporated into the Caledonian orogen and are excellent examples of cold, melt-depleted, LIL-poor, buoyant lithosphere of the type that would be expected beneath the Baltic or Laurentian Shield prior to Caledonian collision.

GP from the Gföhl Nappe in the Bohemian Massif are more complex than the Norwegian peridotites. Relative to Norwegian GP, they are chemically and mineralogically more heterogeneous, some are much more depleted, others are more metasomatized, TP equilibration estimates are much more variable but all formed at significantly higher temperatures, and none give Sm–Nd mineral ages that are significantly pre-Variscan. They seem to represent hot, active mantle that was depleted, metasomatised, recrystallized and stirred by convection shortly before and during the Variscan Orogeny. Some GP (sensu stricto) are believed to represent the lithospheric mantle metasomatized by at least two stages of melt migration that presumably occurred above a subduction zone during the closure of the sea or seas that separated Gondwana and Laurussia. Other "transitional" (i.e. spinel-bearing) GP are believed to represent hot asthenosphere that penetrated the lithosphere and rose to the base of the orogen during the collision of Laurussia and Gondwana, possibly as a result of the delamination of thickened lithosphere. This event provided a thermal pulse that set, or re-set, the ages of many garnet-bearing systems (garnet peridotites, eclogites, granulites) and resulted in the production of enormous amounts of granitoids that characterize the Variscan orogen.

Keywords: garnet peridotite, high-pressure metamorphism, Sm–Nd, collision belt, Norwegian Caledonides, Czech Variscides.

Introduction

Orogenic peridotite massifs, formerly referred to as Alpine-type peridotites, are ubiquitous features of mountain systems. Most are spinel-bearing peridotites or their retrograded, hydrous equivalents (commonly serpentinites). Garnet-bearing peridotites are much less common, but where they do occur, they are associated with eclogites and other high-grade crustal rocks in high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic terranes. Several of the ten or so known UHP terranes (COLEMAN and WANG, 1995) contain garnetiferous ultramafic rocks (for example,

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Kokchetav Massif, Northern Kazakhstan; Western Gneiss Region, Norway; Dabie Shan/Su Lu, China; the Variscides of central Europe). We think it likely there is a genetic relationship between HP/UHP terranes and garnet peridotites. Specifically, we think crustal terranes can be shoved, pulled or sheared into the mantle to depths > 120 km along subduction systems, where they are juxtaposed against garnetiferous mantle rocks in the eclogite facies. This juxtaposition makes it possible for eclogite facies crustal rocks formed by prograde metamorphism in the subducted terrane to mix with pre-existing deep-level rocks from the mantle (garnet peridotites and related garnet pyroxenites and mantle eclogites). These mixed rocks are then exhumed to the surface by erosion and/or extensional tectonics to fuel the often bitter controversy of "in situ" versus "exotic" eclogites, a debate that may be resolved in favor of both sides!

In any case, garnet peridotites offer a window into the deep mantle associated with convergent plate boundaries. Our comparison of garnet-bearing peridotites from two different terranes makes it clear to us that this mantle can vary significantly between orogens. We present initial results of a study of garnet-bearing ultramafic rocks from the UHP Western Gneiss Region (WGR) of the Norwegian Caledonides and the HP Gföhl nappe in the Bohemian Massif (BM) of the central European Variscides (Fig. 1). Both terranes contain garnet peridotites that clearly originated in the upper mantle before becoming entrained in the orogenic systems, but despite superficial similarities, the two suites of ultramafic rocks had very different origins and histories. Norwegian garnet peridotites apparently sat in a cold, static mantle environment for a very long time (> 1 Ga) before they were incorporated into the Caledonian orogen and are excellent examples for cold, melt-depleted, LIL-poor, buoyant lithosphere of the type that would be expected beneath a shield, whereas garnet peridotites from the Gföhl Nappe represent hot, active mantle that was depleted, metasomatised and recrystallized, both in spreading environments and above subduction zones, shortly before and during the Variscan Orogeny.

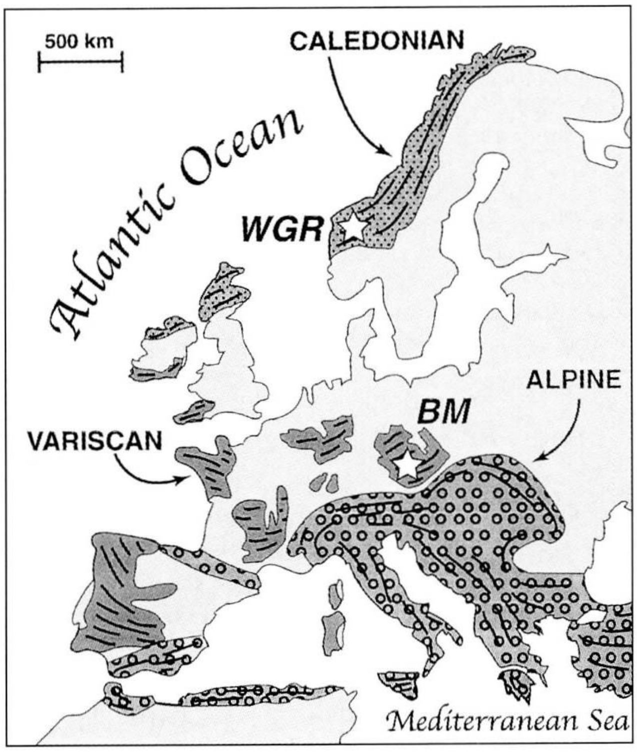

Fig. 1 Distribution of the Caledonian, Variscan and Alpine orogenic belts in Europe and locations of the Western Gneiss Region (WGR), Norway, and the Bohemian Massif (BM), central Europe.

Regional geology

WESTERN GNEISS REGION, NORWAY

The Caledonides are a north–south trending, Early to Middle Paleozoic mountain system that evolved during closure of the Iapetus ocean basin and the ultimate Late Silurian collision of a western continent, Laurentia, with an eastern continent, Baltica. The collision is generally viewed as involving the westward subduction of the Baltic Shield beneath Laurentia (CUTHBERT and CARSWELL, 1990; WIKS and CUTHBERT, 1994; ANDERSEN et al., 1991), a view based in large part on the presence of eclogite-facies rocks in Norway (KROGH and CARSWELL, 1995). However, a large Caledonian eclogite-province has been delineated in North-East Greenland (GILOTTI, 1993), and this simple model will no doubt be revised.

The WGR in southwest Norway (Fig. 1) is well-known in the geological literature (see KROGH and CARSWELL, 1995 for the most recent review) for its spectacular and abundant eclogite *(sensu stricto)* boudins that formed the basis for ESKOLA'S (1924) classic work on the eclogite facies. A long-standing debate over whether these high pressure rocks were "exotic", i.e. formed in the mantle and then tectonically inserted into the crust, or metamorphosed *in situ* while in their present tectonic position in the crust during the Caledonian orogeny, appeared to be resolved in favor of the *in situ* origin, when it was shown that the eclogites formed at pressures and temperatures appropriate to Ampferer-type subducted continental crust (KROGH, 1977; GRIFFIN et al., 1985). Other evidence supporting an *in situ* origin include: mineral zoning patterns that give "clockwise" TP histories appropriate to subduction, a regional distribution of eclogite TP conditions that is consistent with increasing subduction depths from east to west (KROGH, 1977), a common structural history for eclogites and surrounding gneisses (BRYHNI, 1966; BRUECKNER, 1969, 1977a), and crustal isotopic signatures (BRUECKNER, 1977b) and Caledonian crystallization ages (410–425 Ma or upper Silurian; GRIFFIN and BRUECKNER, 1980, 1985; GEBAUER et al., 1985) for the eclogites. Perhaps the most compelling evidence was the discovery of relict HP mineral assemblages in the gneisses and metasediments enclosing the eclogites, demonstrating that the eclogites and the enclosing felsic crustal rocks were isofacial under HP metamorphic conditions, prior to extensive amphibolite facies overprinting (see CUTHBERT and CARSWELL, 1990, for review).

Coesite and coesite pseudomorphic textures have been recognized in numerous eclogites (see SMITH, 1988, for a review; WAIN, 1997), as well as in the enclosing gneisses (WAIN, 1997). Microdiamonds have been reported from one gneiss locality (DOBRZHINETSKAYA et al., 1995), although *in situ* occurrence of diamond remains to be demonstrated. These discoveries raise the status of the WGR, or at least portions of it, from that of a mere HP terrane to that of an UHP metamorphic terrane. Subduction of the WGR to depths of at least 120 km cannot be achieved by simply stacking one 40 km-thick continent over another of equivalent thickness. Somehow the WGR was shoved, pulled or sheared into deeper levels of the upper mantle, presumably along a subduction zone. Recognition of the UHP status of the WGR resolves an anomaly stressed previously by advocates of the "exotic" eclogite model (LAPPIN, 1977; O'HARA, 1976, LAPPIN and SMITH, 1981, SMITH, 1988), namely the presence of garnet peridotites within the WGR. These peridotites are not only of obvious mantle derivation, but also crystallized at high TP conditions of ~ 800 °C, 30–55 kbar (MEDARIS and CARSWELL, 1990; KROGH and CARSWELL, 1995). A mechanism for bringing such high-pressure peridotites up into the crust is lacking in simple Ampferer subduction models, but seems more tractable if the crust reached the deep mantle levels where these peridotites resided.

BOHEMIAN MASSIF, CENTRAL EUROPE

The Variscan Orogen is a Middle to Late Paleozoic mountain system exposed in a series of massifs that extend east-west across Europe, among which the Bohemian Massif (BM) is the easternmost (Fig. 1). The orogen evolved through the closure of one or more ocean basins (Tornquist Sea, Rheic Ocean, Theic Ocean) and the Carboniferous collision of a northern continent, Laurussia, with the southern Gondwana continent (REY et al., 1997). The collision was preceded by the amalgamation of microplates (Avalonia and Amorica), volcanic arcs, and small ocean basins along the margins of Laurussia and Gondwana from Late Ordovician to Early Carboniferous time (REY et al., 1997). These precursor accretions may have been responsible for introducing complex mantle from a variety of tectonic settings into the final orogenic environment. A notable difference in the evolution of the Variscides compared to the Caledonides was a major late-stage thermal pulse marked by HT-LP metamorphism and the intrusion of large volumes of granitoids.

Eclogites are relatively common in the Bohemian Massif (DUDEK and FEDIUKOVÁ, 1974; O'BRIEN et al., 1990; MEDARIS et al., 1995a); they occur in the Moldanubian Zone, which is a collage of crystalline tectonostratigraphic units or nappes that form the high-grade core of the Bohemian Massif, and in terranes of the external Saxothuringian Zone, such as the Erzgebirge Crystalline Complex, Snieznik Complex, Münchberg Gneiss Complex, etc. (see SCHMÄDICKE and EVANS, 1997, for a recent review). Coesite has been described from two eclogite localities in the Saxothuringian Zone (BAKUN-CZUBAROW, 1991; SCHMÄDICKE, 1991), indicating UHP metamorphism for this external zone, but coesite has not been found so far in the internal Moldanubian Zone.

Among the various Moldanubian terranes, garnet peridotites occur only in the Gföhl Nappe, which is the highest tectonic unit in the zone. The Gföhl Nappe is characterized by HP felsic granulite (Weissstein, or leptynite), which gives maximum TP conditions of ~1000 °C, 16 kbar (CARSWELL and O'BRIEN, 1993). Eclogite is rare in the Gföhl Nappe, due to extensive retrograde recrystallization to amphibolite, but a recent discovery of relict eclogite, which yields minimum TP conditions of 890 °C, 18.0 kbar (MEDARIS et al., in press), demonstrates that felsic and mafic crustal rocks in the Gföhl Nappe experienced eclogite facies conditions. In addition, calcsilicate assemblages in marbles associated with granulites in Lower Austria indicate pressures on the order of 30–40 kbar (BECKER and ALTHERR, 1992) and suggest that parts of the Gföhl Nappe may have been subject to UHP metamorphic conditions.

Eclogites, garnet granulites, garnet peridotites and garnet pyroxenites within the Gföhl Nappe generally give Variscan Sm–Nd mineral ages

(324–373 Ma; CARSWELL and JAMTVEIT, 1990; BRUECKNER et al., 1991; BEARD et al., 1992; MEDARIS et al., 1995b; BECKER, 1997). The younger group of ages are consistent with Carboniferous U–Pb zircon and Sm–Nd mineral ages from the associated HP felsic granulites (VAN BREEMEN et al., 1982; AFTALION et al., 1989; KRÖNER et al., 1988; BECKER, 1987). The significance of these dates is discussed later in this paper.

Peridotites

WESTERN GNEISS REGION, NORWAY

There are hundreds of peridotite bodies in the WGR, most of which were recrystallized during the Caledonian Orogeny from garnet-bearing assemblages to chlorite peridotite, containing the assemblage olivine-enstatite-tremolite-chlorite. However, some peridotites still contain garnet, enstatite and diopside, and locally, cm- to dm-size olivine porphyroclasts, which are relicts of the precursor ultramafic assemblage. It is likely that all peridotites in the western part of the WGR were garnet-bearing at some early stage, but were subsequently recrystallized to chlorite peridotite (MEDARIS, 1984). In chlorite peridotite, enstatite and tremolite prisms and chlorite flakes define a penetrative ultramafic schistosity and mineral lineation that parallel similar fabrics in the gneisses. The peridotites also contain several generations of folds that are identical to folds in the enclosing gneisses (BRUECKNER, 1969; MEDARIS, 1980). These structures indicate that the peridotites and gneisses shared a common ductile structural history during much, if not all, of the Caledonian orogeny.

Garnet peridotite, consisting of olivine, low-Al enstatite, Cr-diopside, and pyrope-rich garnet, is preserved in ten or so peridotite bodies, and several others contain amphibole-spinel kelyphite after garnet (see Fig. 1 in MEDARIS, 1984). Locally, garnet peridotites contain lenses and layers of garnet websterite and garnet clinopyroxenite, which indicate one or more periods of melt intrusion while the peridotites were still in the mantle. Some garnet-bearing assemblages are associated with primary hydrous phases such as phlogopite and kaersutitic amphibole, suggesting the possibility of hydrous metasomatism, again while the peridotites were still in the mantle.

Caledonian overprinting of the garnetiferous mantle assemblage in the peridotites has resulted in several stages of recrystallization, the most important of which are (MEDARIS and CARSWELL, 1990):

I	Ol + Opx + Cpx + Grt Proterozoic mantle assemblage
II	Ol + Opx + Cpx + Grt + Spl Caledonian eclogite facies
III	Ol + Opx + Cpx + Spl Caledonian kelyphitic granulite facies
IV	Ol + Opx + Amp + Spl Caledonian coronitic amphibolite facies
V	Ol + Opx + Amp + Chl Caledonian regional amphibolite facies

BOHEMIAN MASSIF

Spinel peridotites occur within most units of the Moldanubian Zone as well as in several of the external crystalline terranes (SCHMÄDICKE and EVANS, 1997). Garnet peridotites, on the other hand, occur only in the Gföhl nappe (GN) of the Moldanubian Zone (CARSWELL, 1991; MEDARIS et al., 1990; BECKER, 1996a, 1996b) and in two external terranes: HP-unit 1 of the Erzgebirge Crystalline Complex (SCHMÄDICKE and EVANS, 1997) and the Sowie Góry Complex (BAKUN-CZUBAROW, 1983; BRUECKNER et al., 1996). The thirty or so garnet-bearing peridotites within the GN can be divided into two groups: (1) garnet peridotite *sensu stricto*, which has no pre-existing spinel and which contains layers and lenses of garnet pyroxenite and HT eclogite, and (2) spinel-garnet peridotite, which is devoid of eclogite layers and in which spinel grains are included within garnets, indicating that the garnetiferous assemblage formed from pre-existing spinel peridotite (CARSWELL, 1991; MEDARIS et al., 1990; BECKER, 1996b). The interiors of some spinel-garnet peridotites, most notably the Mohelno body in the Czech Republic, are entirely spinel peridotite, and garnet occurs only in the margins of the bodies. Garnet-bearing peridotites within the leptynitic granulites (similar to the GN) of the Vosges Mountains (a Variscan Massif in France) fall into two nearly identical categories (ALTHERR and KALT, 1996). Garnet-bearing peridotites within another Variscan Massif, the Schwarzwald in Germany, fall into two groups as well, but their similarities to those within the GN and the Vosges are not as well established (KALT et al., 1995; KALT and ALTHERR, 1996).

Garnet peridotites *ss* are allofacial with respect to surrounding orthogneisses, with which they are in fault contact. The degree to which these garnet peridotites have shared a common structural history with the adjacent gneisses is unclear. Tightly to isoclinally folded garnet peridotites have been described from the GN (BECKER, 1996b) and the Erzgebirge (SCHMÄDICKE and EVANS, 1997) but it is not known whether these structures developed in the mantle or crust. In contrast, the spinel-garnet peridotites have concordant contacts with the enclosing HP granulites, and both rock types had common metamorphic and deformational histories subsequent to their juxtaposition. It appears that the garnet peridotites *ss* and associated pyroxenites and HT eclogites formed in the mantle prior to incorporation in the crust, similar to the garnet peridotites of the WGR of the Norwegian Caledonides. But the garnet in spinel-garnet peridotites may have been stabilized during or after their juxtaposition with crustal rocks.

Four main stages of recrystallization are recorded in the spinel-garnet peridotites (MEDARIS and CARSWELL, 1990):

I Ol + Opx + Cpx + Spl
High-temperature protolith

II Ol + Opx + Cpx + Grt
Variscan stabilization of garnet

III Ol + Opx + Cpx + Spl
Variscan kelyphitic granulite facies

IV Ol + Opx + Amp + Spl
Variscan kelyphitic amphibolite facies

Peridotite TP conditions and cooling histories

Temperature-pressure (TP) conditions for the garnetiferous assemblages in the Norwegian and Gföhl peridotites were calculated by combining the average of three Fe–Mg exchange thermometers (Grt-Ol, O'NEILL and WOOD, 1979, 1980; Grt-Opx, HARLEY, 1984; Grt-Cpx, POWELL, 1985) with the Al-in-Opx barometer (BREY and KÖHLER, 1990). The results are plotted in figure 2, in which are included for reference, the stability fields for diamond and graphite, coesite and quartz, garnet and spinel peridotite, a dry lherzolite solidus, and two steady-state conductive geotherms, one for 200-km thick lithosphere and another for 100-km thick lithosphere, assuming a 35-km thick crust and taking the lithosphere-asthenosphere boundary to be at 1350 °C.

Garnet peridotite from 9 localities in the Western Gneiss Region of Norway (MEDARIS and CARSWELL, 1990; KROGH and CARSWELL, 1995) plot in a tight array from about 805 °C, 34 kbar to 975 °C, 54 kbar. These TP values illustrate that the Norwegian garnet peridotites were derived from relatively cold lithosphere, from depths within the diamond stability field. The restriction of these garnet peridotites to a small area in TP space suggests they were derived from a relatively restricted and static region in the mantle.

In contrast, peridotites from 8 bodies (MEDARIS and CARSWELL, 1990) in the GN yield a wide range of temperatures and pressures, partly overlapping those for the Norwegian peridotites, but extending to temperatures above 1200 °C. Garnet peridotites *ss* (e.g., Bečváry, Biskupice, and Nové Dvory) are most similar to Norwegian peridotites and lie close to the 200-km lithosphere geotherm, but spinel-garnet peridotite (e.g., Mohelno) plots close to the 100-km lithosphere geotherm, in the vicinity of the garnet-spinel peridotite transition. The single determination for Austrian peridotites (A in Fig. 2) is CARSWELL's (1991) estimate of conditions for the P_{max} ultramafic assemblage in this part of the GN. However, both garnet *ss* and spinel-garnet peridotites occur in Austria, as they do in the Czech Republic, and if plotted individually, they would also tend to fill in the TP field for Gföhl peridotites. The diffuse scatter of garnet peridotites from the GN contrasts sharply with the tight clustering of the WGR garnet peridotites, suggesting not only different origins and histories for the peridotites from the two orogens, but also varied origins and histories for the garnet peridotites from the GN. We take this variability in TP space to indicate that the mantle was in motion shortly before and during the Variscan orogeny and that this active stirring resulted in garnet peridotites that had equilibrated in a variety of depth/temperature environments. The tight distribution of Norwegian garnet peridotites along a single "cold" geotherm, on the other hand, suggests a static mantle that was not convecting and equilibrating prior to intermingling of the peridotites with continental crust of the WGR during the Caledonian Orogeny.

Cooling rate calculations suggest different exhumation histories for the peridotites. The rates are based on numerical modeling of compositional zoning in garnets adjacent to olivine inclusions (MEDARIS and WANG, 1986; MEDARIS et al., 1990). It has been found that garnet compositional profiles can be matched closely with bilinear cooling histories. Recalculation of cooling rates, using more recently determined values for cation diffusion in garnet (CHAKRABORTY and GANGULY, 1992; CHAKRABORTY and RUBIE, 1996), yield extremely rapid *initial* cooling rates for the Mohelno spinel-garnet peridotite (70 000 °C/Ma) and the Nové Dvory garnet peridotite *ss* (50 000 °C/Ma), and slower rates for the Norwegian Almklovdalen garnet peridotite (100 °C/Ma). Such large differences in cooling rates between

Norwegian garnet peridotites and those in the GN presumably reflect fundamentally different processes of uplift and exhumation and also imply that the peridotites originated in different types of mantle environments. Three proposed cooling histories are shown in figure 3. The garnet peridotites *ss* from both terranes are believed to have undergone early isothermal decompression from deep mantle levels, followed by cooling and decelerating decompression, whereas the spinel-garnet peridotites from the GN are suggested to have undergone early isobaric cooling from very high temperatures, followed by cooling during decelerating decompression. Even though the garnet peridotites *ss* show similar early decompression histories, those from the GN were derived from a mantle that was significantly hotter than the mantle that produced the garnet peridotites from the WGR. Because of the hotter mantle environment, the garnet-bearing assemblages within the GN peridotites and associated pyroxenites and eclogites either formed or completely re-equilibrated only a few tens of millions of years before the exhumation process began, whereas the colder garnet peridotites from the WGR retained ages that preceded exhumation by over a billion years (see below).

Peridotite chemistry

Whole rock major and trace element patterns from garnet peridotites of both regions generally show a trend consistent with the peridotites as depleted residua caused by partial fusion and extraction of basaltic melts; i.e. SiO_2, Al_2O_3, CaO, Na_2O, TiO_2, and incompatible trace elements decrease, and compatible elements such as Ni and Co increase, with an increase in MgO (BEARD et al., 1992; SCHARBERT and CARSWELL, 1983; BECKER, 1996b). For example, figure 4 shows the depletion trends for CaO *versus* increasing MgO. The depletion trend for the Norwegian garnet peridotites, shown as open circles, are colinear

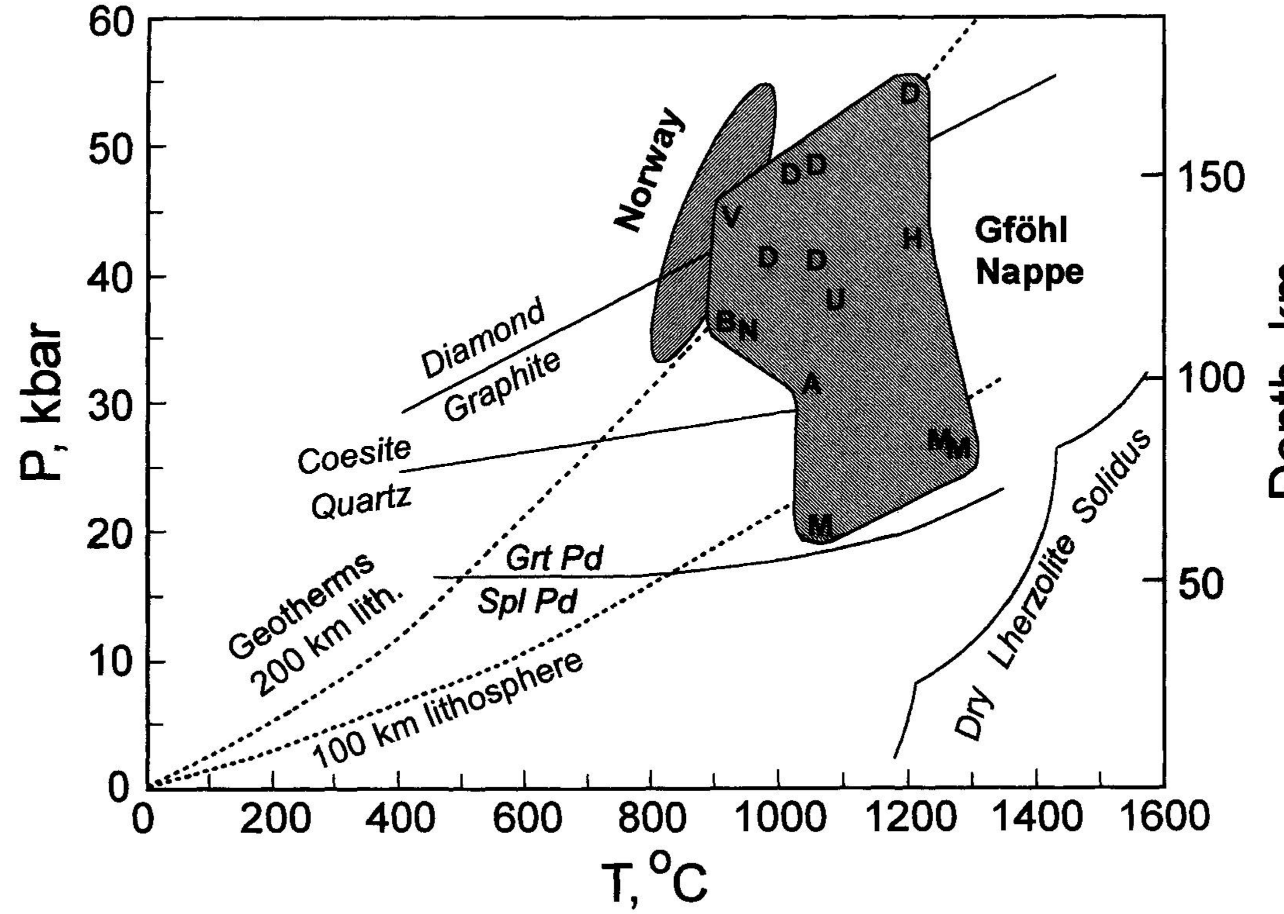

Fig. 2 Temperature-pressure conditions for garnet peridotites from the Western Gneiss Region, Norway and the Gföhl nappe of the Bohemian Massif (taken from MEDARIS and CARSWELL, 1991). Sample designations: A, average of Austrian localities (CARSWELL, 1991); B, Biskupice; D, Nové Dvory; H, Hamry; M, Mohelno; N, Níhov; U, Úhrov; V, Bečváry. Steady-state conductive geotherms for 100- and 200-km thick lithosphere are shown for reference.

with the well-documented trend for the Ronda peridotite (shaded region in Fig. 4; Frey et al., 1985), but extend this trend towards both lower and higher MgO concentrations. The spinel-garnet peridotites from the GN, represented by data from the Mohelno Body, also fall along the Ronda trend, suggesting a geochemical affinity with the Norwegian garnet peridotites *ss*, despite their very different TP histories (Fig. 3).

Surprisingly, the Nové Dvory garnet peridotite *ss* from the GN, which shows a somewhat similar TP history with the Norwegian garnet peridotites, defines a significantly more depleted trend than the garnet peridotites from Norway, with markedly lower contents of CaO (Fig. 4) and Al_2O_3, Sc and Yb (not shown), and higher contents of Ni and Co (not shown) for a given MgO number. Because the major element chemical trends for mantle residua are not significantly different, whether produced by partial melting in the spinel peridotite or garnet peridotite stability fields (see partial melting vectors in Fig. 4), the displacement of the Nové Dvory compositions from the primitive mantle-Ronda-Norway array suggests that the Nové Dvory peridotite may have been derived from a compositionally distinct mantle reservoir.

Additional differences in chemical composition between garnet peridotites in the WGR and GN are illustrated by plotting the Cr_2O_3 and CaO contents of garnet (Fig. 5). Griffin et al. (in press) have demonstrated a secular change in the chemical composition of the mantle, which is documented by the compositions of Archean, Proterozoic, and Phanerozoic garnet lherzolite xenoliths, and which is reflected in the compositions of constituent garnet grains. With respect to Cr_2O_3 and CaO contents, there is a clear separation between garnets from WGR and GN lherzolites, with WGR garnets plotting within the field for Precambrian cratonic xenoliths, and most GN garnets plotting close to, but slightly displaced from, the field for Phanerozoic lherzolite xenoliths. However, garnet from garnet peridotite *ss* in the GN has a greater compositional range than that from

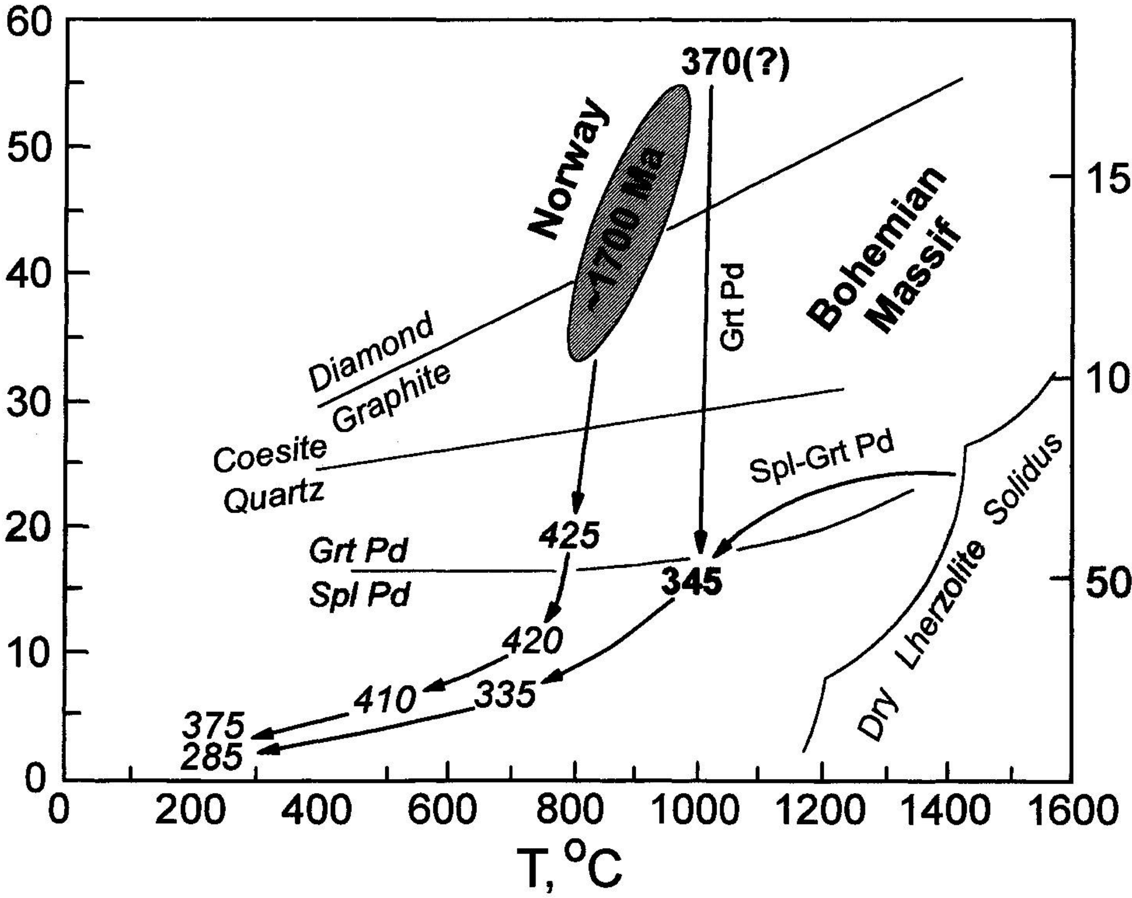

Fig. 3 Temperature-pressure-time paths for peridotite from the Western Gneiss Region, Norway, and for garnet peridotite *ss* and spinel-garnet peridotite from the Gföhl Nappe, Bohemian Massif. Bold, upright numbers: proposed Sm–Nd closure ages for garnetiferous assemblages; italicized numbers: ages of various exhumation stages, based on $^{40}Ar/^{39}Ar$ analyses of amphiboles and micas in associated country rocks (Dallmeyer et al., 1992a, 1992b; Wilks and Cuthbert, 1994).

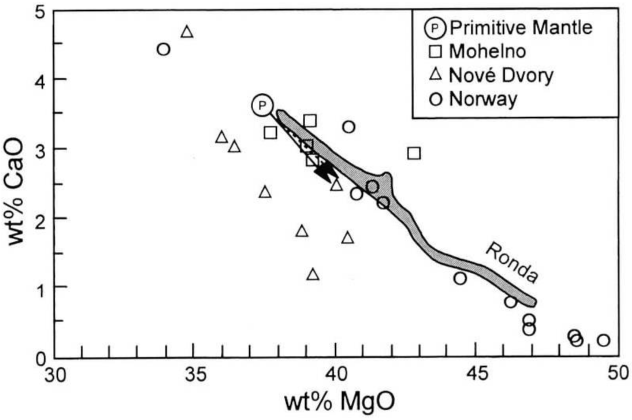

Fig. 4 Variation of CaO with MgO in peridotites from the Western Gneiss Region, Norway and the Gföhl Nappe, Bohemian Massif: Mohelno, spinel-garnet peridotite; Nové Dvory, garnet peridotite *ss;* data for Ronda from FREY et al. (1985) and for primitive mantle from SUN and MCDONOUGH (1989). Arrows indicate compositional trends for residua produced by extraction of melts derived from non-modal batch melting of garnet peridotite (dotted arrow) and spinel peridotite (solid arrow).

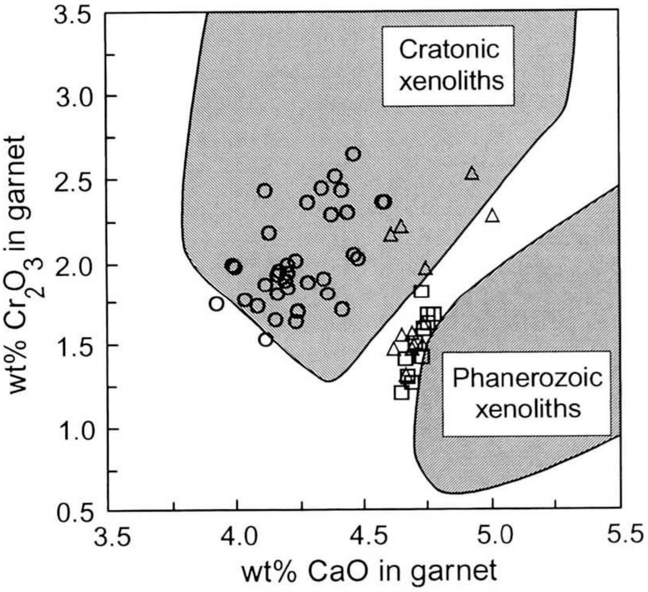

Fig. 5 Concentrations of Cr_2O_3 and CaO in garnet from Norwegian garnet peridotites (circles), Gföhl garnet peridotites *ss* (triangles) and Gföhl spinel-garnet peridotites (squares); data from MEDARIS, 1984; MEDARIS et al., 1990; MEDARIS, unpublished. Fields for garnets from cratonic and Phanerozoic garnet lherzolite xenoliths are taken from GRIFFIN et al., 1998.

spinel-garnet peridotite and locally extends into the field for cratonic xenoliths, further illustrating the variability of peridotites in the GN, with respect to chemical composition, as well as thermal history.

REE patterns for garnet peridotites from both the WGR and the GN generally agree with the melt extraction model, showing progressive overall concentration decreases and greater LREE depletions with increasing MgO (patterns 4 and 5 Fig. 6A). However, other patterns from both terranes are enriched in LREE (patterns 2 and 3, Fig. 6A) suggesting metasomatism of the peridotites in the mantle. Some peridotites from Norway (Lien, Almklovdalen) have curious "hooked" or "Z" patterns (pattern 1, Fig. 6A) indicating multiple processes (depletion followed by metasomatism followed by melting?) that have not yet been found in peridotites from the GN. GN garnet peridotites, on the other hand, particularly harzburgites, show very deep "U" shaped patterns (pattern 6, Fig. 6A; BECKER, 1996b) suggesting extreme melting and depletion of the MREE and LREE, followed by reintroduction of LREE by metasomatism (BECKER, 1996b).

Garnet peridotites adjacent to garnet pyroxenites from both terranes have patterns that mirror, at lower REE concentrations, the patterns of the pyroxenites (Fig. 6B), indicating that at least one episode of metasomatism was caused by the intrusion of pyroxenite melts. BECKER's (1996a) very detailed study of garnet pyroxenites from the GN in Austria suggests that these melts were CO_2-rich magmas strongly enriched in incompatible elements derived from sub-lithosphere depths (> 100–120 km) that intruded the host garnet peridotites *ss* at temperatures of 1100–1400 °C. His study also suggests that pyroxenites and peridotites were locally mixed by shearing, creating hybrid rocks with trace element and isotopic characteristics of both rock types. A possible difference between WGR and GN garnet peridotite REE patterns is that both positive and negative Eu-anomalies occur in the pyroxenites and adjacent peridotites of the GN. Such Eu-anomalies suggest the presence of plagioclase either in the formation of source rock for the pyroxenite melts or in the pyroxenite melts, themselves, implying that they subsequently recrystallized to garnet pyroxenites. Both MEDARIS et al. (1995b) and BECKER (1996 a, b) suggest that subducted upper crustal rocks were involved in the melting that produced the pyroxenite melts of the GN.

Isotopes and "age" patterns

WESTERN GNEISS REGION, NORWAY

Perhaps the most striking contrasts between the two garnet peridotite bearing terranes are in Sr and Nd isotope patterns and apparent Sm–Nd mineral ages. Present-day Sr and Nd isotopic ratios measured from clinopyroxenes from Norwegian garnet peridotites are variable and complex (filled symbols, Fig. 7; Brueckner, 1974; Griffin and Brueckner, 1985; Jamtveit et al., 1991; Brueckner et al., 1996; Brueckner, unpublished data), but suggest depletion and intrusion/metasomatic events that occurred long before the Caledonian Orogeny. Clinopyroxene exsolved from a large orthopyroxene porphyroclast (Ø in Fig. 7A) from the Otrøy peridotite has very unradiogenic ^{87}Sr/^{86}Sr (0.7015) and a high ^{143}Nd/^{144}Nd ratio with a large positive ε_{Nd} value of +28. Three other garnet peridotites show similar, if less extreme, depleted patterns. One clinopyroxene from Otrøy has a reported ε_{Nd} value of > +100 (Jamtveit et al., 1991; not plotted because it would distort the scale on Fig. 7). These values im-

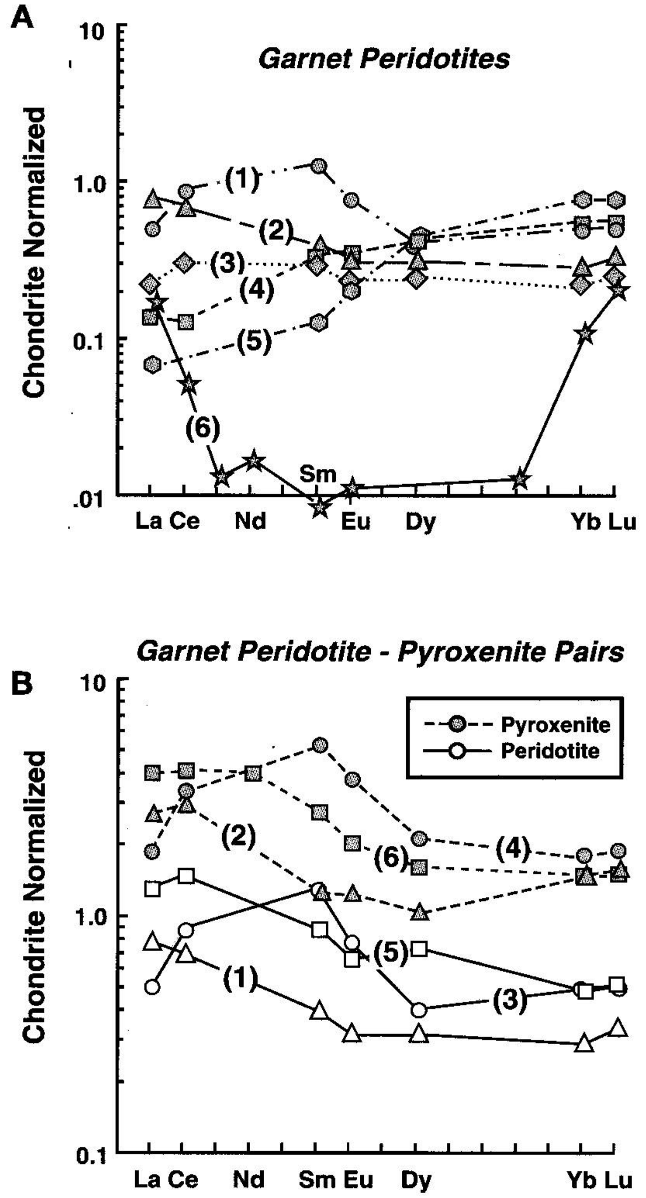

Fig. 6 Representative chondrite-normalized REE contents of garnet peridotites and garnet pyroxenites from the Western Gneiss Region, Norway and the Gföhl Nappe, Bohemian Massif, Czech Republic (Medaris et al., 1995b; Medaris, unpublished).

(A) Depleted garnet peridotites from Aldalen, Norway (5), and Mohelno (4) and Nové Dvory (3), Czech Republic; LREE-enriched (2) and Z-pattern (1) garnet peridotites, Lien, Norway. The U-shaped REE pattern (6) is from a garnet harzburgite, Austria (Becker, 1996a).

(B) Parallel REE patterns from peridotite (open symbols) and pyroxenite (filled symbols) pairs from Lien, Norway (1) and (2) and (3) and (4), and Nové Dvory, Czech Republic (5) and (6).

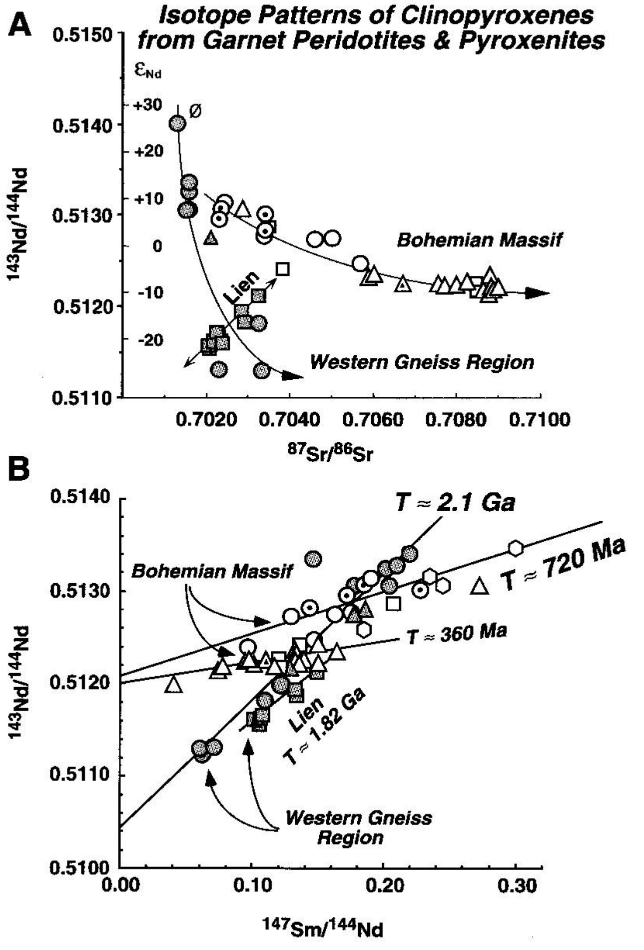

Fig. 7 Sr–Nd covariance diagram (A) and Sm–Nd isochron diagram (B), showing different patterns for clinopyroxenes from garnet peridotites and pyroxenites from the Western Gneiss Region, Norway (filled symbols), compared to those from the Bohemian Massif (open symbols). Norway data: Brueckner, 1974; Griffin and Brueckner, 1985; Jamtveit et al., 1991; Brueckner et al., 1996; Brueckner, unpublished. Bohemian Massif data: symbols with dots, Beard et al., 1992; Brueckner et al., 1991, 1996; open symbols, Schmädicke et al., 1995; Becker, 1996a, 1996b. Circles are peridotites, triangles are pyroxenites, and squares are mixed peridotites/pyroxenites. Hexagons are whole rock analyses from samples lacking clinopyroxene.

ply the event(s) that depleted the WGR peridotites occurred during, or prior to, the Proterozoic, and RUBENSTONE et al. (1986) and JAMTVEIT et al. (1991) have proposed an Archaean mantle melting event between 3000–2500 Ma.

Most other values from Norwegian peridotites scatter along a trend consistent with mixing of the depleted mantle with a component of low $^{143}Nd/^{144}Nd$, but only slightly radiogenic $^{87}Sr/^{86}Sr$. The low ε_{Nd} implies mixing with a relatively ancient LREE-enriched component, but with a low Rb/Sr ratio, otherwise the $^{87}Sr/^{86}Sr$ ratios of the clinopyroxenes would have been significantly higher than they are today (< 0.7032). A possible mixing end member could have been Proterozoic or older lower crustal, granulite-facies rocks. The mixing event is presumed to reflect metasomatism related to the intrusion of pyroxenites. However, smaller scale variations associated with one of these pyroxenite complexes from Lien, Almklovdalen suggest otherwise. These pyroxenites and the adjacent peridotites have the similar REE patterns noted above (i.e. patterns 1 and 2 in Fig. 6B), indicating that the pyroxenites metasomatised the peridotites. But the Lien peridotites and pyroxenites (Fig. 7A) show a positive correlation between $^{87}Sr/^{86}Sr$–$^{143}Nd/^{144}Nd$, instead of the overall negative correlation shown by the rest of the Norwegian garnet peridotites and pyroxenites. These data suggest that at least two different mixing events affected the garnet peridotites from the WGR; the resulting strongly positive and negative present-day ε_{Nd} values indicate that these mixing events were produced long before the Caledonian Orogeny.

Further evidence for the antiquity of these mixing events derives from the fact that clinopyroxenes from Lien define a linear array on Sm–Nd isochron diagram (Fig. 7B) with a best fit "age" of ~ 1.82 Ga. The clinopyroxene array potentially dates the time of intrusion of the pyroxenites and the associated metasomatism, if it is assumed that clinopyroxene REE concentrations and Nd isotope ratios accurately reflect the concentrations

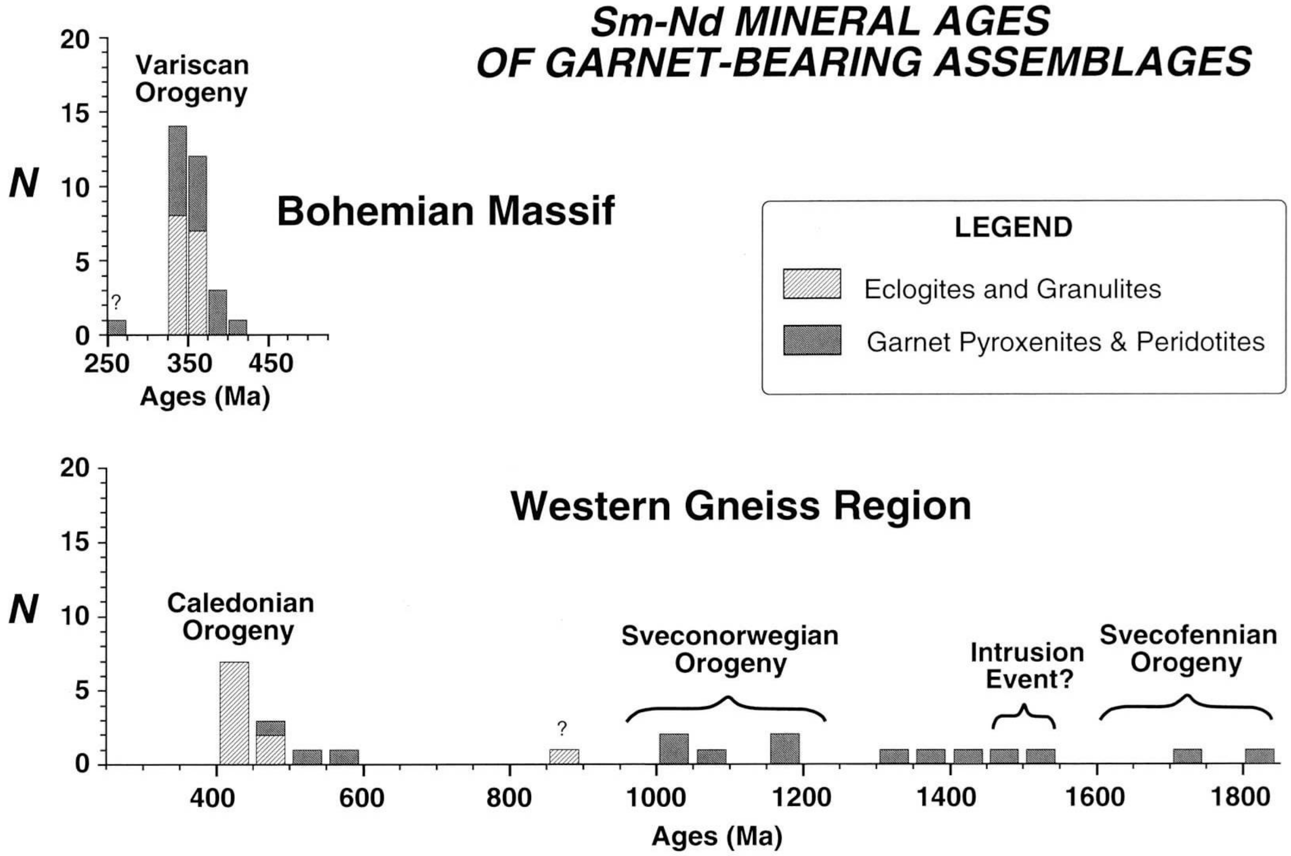

Fig. 8 Histogram showing tightly clustered Sm–Nd mineral ages of garnet peridotites and pyroxenites and of eclogites and HP granulites from the Bohemian Massif, whereas ages from garnet peridotites and pyroxenites from the Western Gneiss Region, Norway, are widely scattered and much older than ages from eclogites. Norwegian data: JACOBSEN and WASSERBURG, 1980; MEARNS and LAPPIN, 1982; MEARNS, 1986; RUBENSTONE et al., 1986; JAMTVEIT et al., 1991; BRUECKNER et al., 1996; and BRUECKNER, unpublished. Bohemian Massif data: CARSWELL and JAMTVEIT, 1990; BRUECKNER et al., 1991, 1996; BEARD et al., 1992; MEDARIS et al., 1995b; SCHMÄDICKE et al., 1995; BECKER, 1997.

and ratios of the bulk rock. The evidence for ancient depletion and mixing events is consistent with a very old recrystallization age implied by a Sm–Nd mineral (garnet-cpx-wr) date of 1703 Ma from garnet peridotite from another locality in the Almklovdalen Peridotite (MEARNS, 1986; JAMTVEIT et al., 1991). If this date is verified, it would mark a minimum age for the depletion/enrichment processes that have affected the WGR peridotites. However, other Sm–Nd mineral "dates" from Norwegian garnet peridotites and garnet pyroxenites (JACOBSEN and WASSERBURG, 1980; MEARNS and LAPPIN, 1982; MEARNS, 1986; RUBENSTONE et al., 1986; JAMTVEIT et al., 1991; BRUECKNER et al., 1996) generally scatter between 511 and 1526 Ma (Fig. 8), so it is probably premature to accept this age uncritically. Several of these "dates" appear to indicate a mantle recrystallization event at roughly 1.0–1.2 Ga and 1.3–1.55 Ga, although it could be argued that these "dates" are mixed ages caused by the partial re-equilibration of ca 1.7 Ga assemblages during the 430 Ma Caledonian orogeny.

Despite the age uncertainties, the striking feature of Sm–Nd mineral dates from WGR garnet peridotites is that they generally predate the Caledonian orogeny, many by over 1000 million years. Only three Sm–Nd mineral ages from peridotites can be considered nearly Caledonian, and they are from secondary garnet-bearing assemblages (i.e. Assemblage II in the 5-stage recrystallization history of WGR peridotites), generally regarded as reflecting Caledonian recrystallization (JAMTVEIT et al., 1991). Even these three ages significantly pre-date the peak of Caledonian metamorphism, taken to be either 425 Ma (GRIFFIN and BRUECKNER, 1980, 1985) or 400 Ma (GEBAUER et al., 1985). The remaining ages attest to the great antiquity of events that affected the mantle source for these peridotites. Many of the ages from the garnet peridotites, in turn, match similar ages in the basement crustal rocks of the WGR (Fig. 8) which are related to the Svecofennian (1600–1750 Ma) and Sveconorwegian (950– 1300 Ma) orogenies and an intrusion event at around 1.5 Ga (BRUECKNER, 1972; PIDGEON and RÅHEIM, 1972; GEBAUER et al., 1985; TUCKER et al., 1990). Both of the pre-Caledonian orogenies were major tectonothermal events responsible for the formation of large volumes of granitic melts from a relatively depleted mantle. It seems reasonable that an event that had such an important tectonothermal effect on the crustal rocks of the Baltic shield would also have a major effect on the rocks of the underlying mantle. This match suggests that the mantle and crust in the southern Caledonides of Norway, as well as other terranes that were adjacent at the time, were coupled throughout much of the Proterozoic.

GFÖHL NAPPE, BOHEMIAN MASSIF

Isotope patterns and Sm–Nd dates from peridotites of the GN (open symbols in Fig. 7; upper histogram in Fig. 8) are strikingly different from those of the WGR, even though major and trace element chemistries of ultramafic rocks from both terranes show roughly similar depletion, intrusion and metasomatic patterns. Present-day Sr–Nd isotopes from clinopyroxenes from the GN, for example, do not show the same degree of depletion (i.e. high $^{143}Nd/^{144}Nd$ or ε_{Nd}, low $^{87}Sr/^{86}Sr$) as clinopyroxenes from the WGR (Fig. 7A; MEDARIS et al., 1995b; BRUECKNER et al., 1991; 1996; BECKER, 1996 a, b). This feature suggests that although the nature and degree of melt extraction might have been similar in both mantle systems, the extraction event(s) occurred more recently in the Variscan mantle than in the Caledonian mantle. Similarly, the mixing lines defined from the two terranes are different. The clinopyroxenes from GN garnet peridotites, like those from the Norwegian garnet peridotites, indicate a mixing trend on a present day Sr–Nd covariance diagram (Fig. 7A), but with a shallow slope relative to the trend of WGR garnet peridotites, and towards much higher $^{87}Sr/^{86}Sr$ ratios.

The GN trend suggests not only more recent mixing processes, but also mixing between fundamentally different end members. Some garnet pyroxenites, for example Níhov in the Czech Republic (MEDARIS et al., 1995b) and the high-Mg pyroxenites with negative Eu anomalies in Austria (BECKER, 1996 a, b), show very high $^{87}Sr/^{86}Sr$ (up to 0.709), but only modestly negative ε_{Nd} (no lower than –4.9). These values contrast with the much lower present day ε_{Nd} and $^{87}Sr/^{86}Sr$ ratios of the Norwegian mixing component, postulated to have been derived from lower crustal rocks. The Sr and Nd isotopic signatures, combined with $\delta^{18}O$ values for clinopyroxene ranging from +3.8 to +5.8‰, suggest the pyroxenite melts that altered the peridotites in the GN were contaminated by an upper crustal component, perhaps fluids from subducted, hydrothermally altered ocean crust and associated sea floor sediments (MEDARIS et al., 1995b; BECKER, 1996b). As was the case in the WGR of Norway, the mixing appears to be related to metasomatism associated with the intrusion of garnet pyroxenite melts (i.e., REE patterns 5 and 6 in Fig. 6B).

Further evidence for an active pre-Variscan mantle comes from linear arrays defined by clinopyroxenes and some whole rocks on a Sm–Nd isochron diagram (Fig. 7B; BRUECKNER et al., 1991; BEARD et al., 1992; BECKER, 1996a, 1996b; BRUECKNER, 1996; data includes results from the Erzgebirge Crystalline Massif, SCHMÄDICKE et al., 1995). The arrays are only crudely colinear, and the best-fit lines are intended more for reference than to indicate true ages. Nevertheless it is striking that the array from the GN is much shallower than that defined by peridotites from the WGR, implying that much of the redistribution of elements and isotopes in the mantle represented by GN ultramafic rocks occurred much more recently than in the mantle represented by WGR peridotites. The difference in age between the Caledonides and the Variscides is only about 100 Ma, and the differences in the arrays of the two orogens cannot be ascribed to the relatively small difference in ages of the orogens. In addition, the peridotites and pyroxenites from the GN appear to define two arrays of different slope and origins. Is it too much to suggest that the roughly late Proterozoic "scatterchron" age defined by the peridotites of the GN might have been related to melt extraction during the opening of a major ocean that separated Gondwana from a northern continent? And could the significantly younger age defined by the pyroxenite scatterchron be related to subduction-related processes during the closing of this and other ocean basins prior to the culminating collision of Gondwana and Laurussia?

Relatively young Sm–Nd mineral ages from the GN garnet peridotites and garnet pyroxenites (325-402 Ma; CARSWELL and JAMTVEIT, 1990; BEARD et al., 1992; MEDARIS et al., 1995; BRUECKNER et al., 1996; BECKER, 1997) are consistent with the suggestion that the mantle sampled by garnet peridotites in the GN underwent major chemical and isotopic perturbations just before and during the Variscan Orogeny. These ages overlap ages defined by eclogites and high-pressure felsic granulites (BRUECKNER et al., 1991, 1996; BEARD et al., 1992; MEDARIS et al., 1995; BECKER, 1997) and contrast with the very old Sm–Nd mineral ages for Norwegian garnet peridotites (Fig. 8). The implication is that garnetiferous assemblages in the peridotites and pyroxenites of the GN formed or were completely re-equilibrated for Sm, Nd and Nd isotopes either during or just a few tens of millions of years before the collision of Gondwana and Laurussia. The significance of the time span represented by the oldest and youngest ages of peridotites, pyroxenites, and crustal rocks from the GN (~ 75 million years) is the subject of vigorous debate (i.e. BRUECKNER, 1991; BECKER, 1997; CARSWELL, 1991; CARSWELL and O'BRIEN, 1993), concerned with distinguishing between different possible episodes of HP and UHP metamorphism and magmatism, but this debate should not obscure the fact that the interval is trivial compared to the interval defined by garnet peridotites from the WGR.

Conclusions

The geochemical, petrological and age characteristics of garnet-bearing peridotites from the Western Gneiss Region of the Norwegian Caledonides and the Gföhl Nappe of the central European Variscides suggest that different types of mantle became entrained in these orogens during their construction by continent-continent collision. Depletion of WGR peridotites by melt extraction may have occurred as long ago as the Archean; subsequent intrusion by pyroxenites and metasomatism probably occurred during one or more cycles during the Proterozoic. Some preliminary Sm–Nd data from cpx (Fig. 7b) from the Lien peridotite at Almklovdalen suggest that intrusion of pyroxenites occurred at ~ 1.82 Ga. A single Sm–Nd garnet-clinopyoxene date from the Almklovdalen body suggests that the peridotites were already in the garnet stability field at 1.76 Ga (MEARNS, 1986). These events may have been related to the Svecofennian orogeny, which had a profound effect on the tectonothermal evolution of the crustal rocks in the WGR. Other Sm–Nd garnet-clinopyroxene ages hint at a major re-equilibration event during the Sveconorwegian orogeny (~ 0.9 to 1.3 Ga; BRUECKNER et al., 1996), which marked a major period of igneous intrusion in the WGR and surrounding areas. The similarity of peridotite ages with those of the associated crustal rocks suggest that the Norwegian garnet peridotites were derived from the lithospheric mantle beneath Baltica and that the mantle and crust in this region were coupled throughout the Proterozoic and the early Paleozoic. There is no evidence that this mantle was affected by any major geochemical or tectonothermal event from the Sveconorwegian orogeny until the peak of the Caledonian orogeny, when Baltica was subducted beneath Laurentia. That there is little evidence for activity prior to Caledonian collision is surprising, because major plate tectonic processes must have been operating in the region at the time, including rifting and opening of Iapetus, subduction and closure of Iapetus, collision of microcontinents, development of volcanic arcs, etc. The static condition of this mantle was interrupted only when subduction of the WGR and its underlying lithosphere beneath Laurentia resulted in the formation of new eclogite-facies mineral assemblages in the garnet peridotites (Assemblage 3 of Medaris, 1984; Stage III of Carswell, 1986), because Sm–Nd dates from these assemblages give roughly Caledonian ages (Jamtveit et al., 1991). If delamination of the lithosphere occurred after Baltica had been subducted to UHP levels (Andersen et al., 1991), it failed to result in the penetration of the asthenosphere, because the WGR and its entrained garnet peridotites appear to have been exhumed without the major heating that characterized the GN.

The static nature of the Norwegian mantle before continent-continent collision contrasts markedly with the geochemically and tectonically active mantle represented by the garnet peridotites of the GN. The chemical depletion of this mantle appears to have occurred in latest Proterozoic or earliest Paleozoic time, as one or more major ocean basins developed between Gondwana and Laurussia. This depleted mantle was subsequently intruded and metasomatized by pyroxenite and eclogite melts; presumably as these ocean basins began to close by subduction. The geochemical fingerprints of subduction-related melting and dehydration seem particularly well developed in the pyroxenites of the GN (Medaris et al., 1995b; Becker, 1996 a, b). The variable TP equilibration conditions recorded in the mineralogies of the GN garnet peridotites and garnet pyroxenites suggest that this mantle was undergoing active motion during this time period, presumably as a result of its position above one or more active subduction zones.

We suggest that at least two types of mantle became emplaced in the Gföhl nappe of the BM during the continental collision that marked the culmination of the Variscan orogeny. The mantle was probably positioned beneath the over-riding continent (Gondwana) and was caught between Laurussia and Gondwana during collision. The garnet peridotites *ss*, typified by the Nové Dvory body, are believed to represent the lithospheric mantle that had been metasomatized by at least two stages of melt migration during the subduction of oceanic lithosphere beneath Gondwana. The spinel-garnet peridotites, represented by the Mohelno body, are believed to represent hot asthenosphere that penetrated the lithosphere and rose to the base of the orogen during the collision of Laurussia and Gondwana. A possible mechanism for the upwelling of asthenosphere might have been delamination of the lithosphere after it had pulled the subducting Laurussia continent to HP conditions. This event provided a thermal pulse that set or re-set the ages of many garnet-bearing systems (garnet peridotites, eclogites, granulites) and resulted in the production of enormous amounts of granitoids that characterize the Variscan orogen.

The garnet peridotites from these two very different mountain systems contain significant information on the geochemical, petrological and structural evolution of the mantle associated with each orogen. This information can be combined with the more broadly available knowledge of the crustal rocks to provide important constraints on the evolution of these mountain systems both during and prior to collision.

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