Conditions and timing of high-pressure Variscan metamorphism in the South Carpathians, Romania

Gordon Medaris Jr. a,*, Mihai Ducea b, Ed Ghent c, Viorica Iancu d

a Department of Geology and Geophysics, University of Wisconsin-Madison, Madison, WI 53706, USA
b Department of Geosciences, University of Arizona, Tucson, AZ 85719, USA
c Department of Geology and Geophysics, University of Calgary, Calgary, Alberta, Canada T2N 1N4
d Geological Institute of Romania, RO-78344 Bucharest 32, Romania

Abstract

High-pressure (HP) metamorphic rocks, including garnet peridotite, eclogite, HP granulite, and HP amphibolite, are important constituents of several tectonostratigraphic units in the pre-Alpine nappe stack of the Getic–Supragetic (GS) basement in the South Carpathians. A Variscan age for HP metamorphism is firmly established by Sm–Nd mineral–whole-rock isochrons for garnet amphibolite, 358 ± 10 Ma, two samples of eclogite, 341 ± 8 and 344 ± 7 Ma, and garnet peridotite, 316 ± 4 Ma.

A prograde history for many HP metamorphic rocks is documented by the presence of lower pressure mineral inclusions and compositional zoning in garnet. Application of commonly accepted thermobarometers to eclogite (grt + cpx ± ky ± phn ± pg ± zo) yields a range in “peak” pressures and temperatures of 10.8–22.3 kbar and 545–745 °C, depending on tectonostratigraphic unit and locality. Zoisite equilibria indicate that activity of H₂O in some samples was substantially reduced, ca. 0.1–0.4. HP granulite (grt + cpx + hb + pl) and HP amphibolite (grt + hbl + pl) may have formed by retrogression of eclogites during high-temperature decompression. Two types of garnet peridotite have been recognized, one forming from spinel peridotite at ca. 1150–1300 °C, 25.8–29.0 kbar, and another from plagioclase peridotite at 560 °C, 16.1 kbar.

The Variscan evolution of the pre-Mesozoic basement in the South Carpathians is similar to that in other segments of the European Variscides, including widespread HP metamorphism, in which P–T–t characteristics are specific to individual tectonostratigraphic units, the presence of diverse types of garnet peridotite, diachronous subduction and accretion, nappe assembly in pre-Westphalian time due to collision of Laurussia, Gondwana, and amalgamated terranes, and finally, rapid exhumation, cooling, and deposition of eroded debris in Westphalian to Permian sedimentary basins.

Keywords: Eclogite; Garnet peridotite; Sm–Nd geochronology; Variscan; South Carpathians

1. Introduction

Eclogite facies metamorphism is a well-documented feature of European Variscan massifs and Variscan basement incorporated in the Alpine belt, providing evidence for the important role played by subduction and continental collision in development of the Variscan orogen (O’Brien et al., 1990). In Romania, eclogite occurs in the pre-Alpine nappe stack of the Getic–Supragetic basement in the South Carpathians, where it was first recognized by Mrazec...
(1897) and subsequently described on a regional basis by Iancu et al. (1988). Geological mapping at a scale of 1:50,000 and accompanying petrological investigations have established the details of eclogite occurrence in several topographic subdivisions of the South Carpathians, including the Fagaras-Leaota Mountains (Gherasi et al., 1971; Dimitrescu and Murariu, 1984; Balaban, 1986; Gheuca and Dinica, 1986; Kasper, 1993; Sabau et al., 1986; Maruntiu et al., 1997), the Mehedinti-Capatana Mountains (Hann, 1983; Iancu et al., 1987; Iancu, 1995), the Sebes-Cindrel Mountains (Maruntiu, 1988), and the Lotru Mountains (Iancu and Maruntiu, 1994).

Geological relations constrain high-pressure (HP) metamorphism in the South Carpathian basement units to be pre-Westphalian in age. Hornblende and muscovite $^{40}$Ar/$^{39}$Ar cooling ages between ca. 320 and 295 Ma for basement units (Dallmeyer et al., 1998) indicate that high-pressure metamorphism was pre-Alpine and most likely Variscan, although the time of HP metamorphism has not yet been determined precisely. Despite several recent petrological investigations (Maruntiu et al., 1997; Iancu et al., 1998; Sabau, 2000), data on high-pressure metamorphism in the South Carpathians remain relatively sparse, compared to that in central Europe.

The present investigation was undertaken to establish the conditions and age(s) of high-pressure metamorphism in the various eclogite-bearing basement units in the South Carpathians. Such information is essential for deciphering the pre-Alpine evolution of the South Carpathians and for documenting the extent of the Variscan orogen in southeastern Europe.

2. Regional geology

The Carpathian Mountains constitute a convex-eastward loop of the Alpine belt, extending from the Austrian Alps through Slovakia, Hungary, and Romania, and rejoining the Dinaric Alps in Serbia. The Carpathians are characterized by thrust and nappe tectonics of Alpine age, with vergence in the South Carpathians being to the south and east. Three main structural units have been recognized in the South Carpathians: a lower Danubian nappe system, consisting of Proterozoic metamorphic rocks and low-grade Paleozoic sedimentary formations, overlain in turn by Westphalian to Permian and Mesozoic sedimentary rocks; a middle Severin–Arjana nappe system, composed of Jurassic ophiolite, flysch, and bimodal alkaline igneous rocks; and an upper Getic–Supragetic nappe system, containing several pre-Alpine basement gneissic units which are overlain by Late Carboniferous to Permian sedimentary rocks and a transgressive Mesozoic cover. The Supragetic unit was thrust over the Getic unit in Lower Cretaceous (pre-Vraconian) time; the Getic–Supragetic nappe system was thrust over the Severin nappe in post-Aptian to Turonian time, and the amalgamated Getic–Supragetic/Severin system was thrust over the Danubian unit in Upper Cretaceous (Senonian) time (Balintoni et al., 1986; Codarcea, 1940; Iancu, 1986; Sandulescu, 1984). Miocene thrusts juxtapose the South Carpathian nappe system against the Moesian platform on the east, while westward thrust faults of the orogen are covered by Neogene sediments of the Pannonian basin.

Eclogite, garnet peridotite, HP granulite, and HP amphibolite in the South Carpathians occur in the pre-Alpine Getic–Supragetic (GS) basement and in a tectonic mélangé, the Bughea complex, at the eastern end of the range, as shown in the simplified geological map of Fig. 1 (modified from Iancu et al., in press). Among the many tectonostratigraphic units in the GS basement, high-pressure rocks are restricted to the Sebes, Lotru, and Cumpana terranes (listed in descending structural position). The reader is referred to Iancu et al. (1998) for a complete description of pre-Alpine basement units in the South Carpathians and a discussion of stratigraphic and structural relations.

The Sebes unit has been divided on the basis of lithology into three subunits, these being 3, 2, and 1 in descending structural sequence. Sebes 3 is composed of a monotonous sequence of aluminous schist and paragneiss, with a few distinctive manganese-rich horizons marked by tephroite- and spessartine-bearing paragneiss. Sebes 2 is characterized by a bimodal suite of quartzofeldspathic gneiss and amphibolite that closely resembles the classic leptynite–amphibolite association in the Massif Central and Bohemian Massif (Matte, 1986; Franke, 1989). Sebes 1 consists predominantly of terrigenous metasedimentary rocks, including mica gneiss, quartzofeldspathic gneiss, and subordinate quartzite, marble, and amphibolite.
Fig. 1. Simplified geological map of the South Carpathians, emphasizing tectonostratigraphic units in the pre-Alpine Getic–Supragetic basement (Sebes, Lotru, and Cumpana), where most high-pressure metamorphic rocks are located. Sample designations: S1, S2, S3, Sebes 1, 2, and 3, respectively; L, Lotru; C, Cumpana; B, Bughea complex.
The Lotru unit is a volcano-sedimentary terrane with oceanic affinities, consisting largely of amphibolite and biotite–plagioclase gneiss. Scattered through the Lotru unit are dismembered layered metabasic–ultrabasic complexes, derived from lherzolite, dunite, plagioclase wehrlite, and gabbro.

Augen orthogneiss is predominant in the Cumpana unit, but subordinate mica schist, biotite paragneiss, and quartzofeldspathic gneiss also occur. Locally, layered metagabbro complexes and felsic gneiss–amphibolite (leptynite–amphibolite) associations are important.

The Bughea complex is a tectonic mélangé located between a lower, polymetamorphic basement of Cumpana type (Voinesti Formation) and an overlying sequence of low-grade Paleozoic metabasic complexes (Calusu and Leresti Formations). Within the mélange, boudins of eclogite, coronitic metagranite, and garnet amphibolite are enclosed by a mylonitic matrix composed of various types of amphibolite, mica schist, and garnet gneiss, which equilibrated under conditions of the epidote amphibolite facies.

Protolith ages of the gneiss units and associated HP rocks in the Getic–Supragetic basement are unknown, although Paleozoic and Proterozoic ages are presumed on the basis of regional geological relations and a few isotopic determinations (Pavelescu et al., 1983; Dragusanu and Tanaka, 1999).

3. South Carpathian high-pressure rocks

As elsewhere in the European Variscides, eclogite, garnet peridotite, HP granulite, and HP amphibolite in the South Carpathians occur as meter- to decameter-sized boudins and larger dismembered bodies, surrounded by various types of gneissic rocks. Eclogite is the medium-temperature type (Carswell, 1990) and commonly contains evidence of a prograde history, such as local preservation of preexisting igneous textures, inclusions of pre-eclogite stage minerals in garnet, and prograde compositional zoning in garnet. Retrograde effects are pervasive, including decomposition of omphacite to symplectite, development of kelyphite and coronas around garnet and kyanite, and extensive recrystallization to amphibolite.

The emphasis of the present study is to determine the conditions and timing of high-pressure metamorphism in the South Carpathians, and toward this end, 26 samples have been investigated. Their most important characteristics are summarized in Table 1, and representative textures and mineralogical features are illustrated on a microscopic scale in Figs. 2 and 3. A detailed evaluation of pre- and post-eclogite stage mineral reactions, although a worthy subject, is beyond the scope of the present reconnaissance investigation.

Eclogite varies in outcrop from massive to layered and texturally from isotropic (L3, Fig. 3) to foliated (S1-1, Fig. 2) and lineated. Eclogite samples from the Danis and Bughita localities in the Bughea complex are notable for having high-pressure phases (omphacite, phengite, kyanite, zoisite) oriented along an S–C type, mylonitic foliation. Garnet, omphacite, and rutile are essential minerals in eclogite, but additional phases, such as quartz, kyanite, zoisite, phengite, or paragonite are stable in some samples (Table 1, Figs. 2 and 3), depending largely on rock chemical composition and equilibration conditions. Pre-eclogite stage minerals, including plagioclase, amphibole, epidote or zoisite, and low-Na clinopyroxene, occur as inclusions in garnet in many eclogites (Table 1). Eclogite is relatively abundant in the Sebes 1, Lotru, Cumpana, and Bughea units, but is rare in Sebes 2 and 3, where high-pressure granulite and amphibolite, perhaps representing overprinted eclogite, are found instead. In this respect, the Sebes 2 and 3 units resemble the Göhl nappe in the Bohemian Massif, in which eclogite is rarely preserved, having been extensively recrystallized to granulite and amphibolite during a later high-temperature overprint (Medaris et al., 1998).

The single sample of garnet granulite analyzed in this study is located in the Sebes Valley in the Sebes 2 unit. Although the granulite yields a relatively high pressure of 11.7 kbar, the presence of plagioclase (Ab78-83) coronas around garnet and intergrowths of Na-poor clinopyroxene, amphibole, and plagioclase (Ab75-81), which resemble coarse-grained symplectite (S2-1, Fig. 2), suggest that the granulite has recrystallized from a higher pressure precursor that contained sodic pyroxene.

Garnet amphibolite (C3, Fig. 2) is commonly associated with eclogite, and textural and field relations indicate that some amphibolites formed by retrograde recrystallization of preexisting eclogites. However, other amphibolite samples, some of which contain rutile, are devoid of textures indicating a prior
eclogite stage and may represent metabasic rocks that recrystallized at relatively high pressures, but less than those of eclogite facies conditions.

Two different types of garnet peridotite are present in the South Carpathians, one at Foltea Peak in the Sebes 3 unit and another at Paltinis in the Lotru unit. The Foltea garnet peridotite is a large, lens-like body ~250 m in length, surrounded by garnet–kyanite mica schist and plagioclase-rich paragneiss. Coarse-grained garnet porphyroblasts, which are typically surrounded by pyroxene–spinel kelyphite, are set in a granoblastic matrix consisting of olivine, orthopyroxene, and clinopyroxene (S3-1, Fig. 2). Although Al-rich spinel inclusions in garnet have been reported (Maruntiu, 1988), they were not observed in the samples examined here. The petrological and miner-

Table 1
Analyzed South Carpathian high-pressure rocks: summary of characteristics

<table>
<thead>
<tr>
<th>Unit and locality</th>
<th>Sample</th>
<th>Lithology</th>
<th>HP assemblage</th>
<th>Garnet zoning (core to rim)</th>
<th>Inclusions in garnet*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sebes 3</strong></td>
<td>Foltea</td>
<td>S3-1 g rt peridotite</td>
<td>grt–opx–cpx–grt</td>
<td>slight retrograde</td>
<td>spl, phl</td>
</tr>
<tr>
<td>Foltea</td>
<td>S3-2 g rt peridotite</td>
<td>grt–opx–cpx–grt</td>
<td>slight retrograde</td>
<td>spl</td>
<td></td>
</tr>
<tr>
<td><strong>Sebes Valley</strong></td>
<td>S2-1 g rt granulite</td>
<td>grt–cpx–am–pl–q–ttn–op</td>
<td>slight ↓sp↑grs</td>
<td>pl, am, ttn, q</td>
<td></td>
</tr>
<tr>
<td>S2-2 g rt amphibolite</td>
<td>grt–am–pl–ep–q–op–ttn</td>
<td>slight ↑prp ↓grs</td>
<td>pl, am, ep, q</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sebes 1</strong></td>
<td>Mehedinti</td>
<td>S1-1 ky eclogite</td>
<td>grt–omp–ky–rt–op</td>
<td>slight ↑prp ↓grs</td>
<td>am, zo, kyb, omp</td>
</tr>
<tr>
<td>Mehedinti</td>
<td>S1-3 zo–ky eclogite</td>
<td>grt–sympy–ky–zo–q–rt–op</td>
<td>slight ↓alm, prp ↑grs</td>
<td>pl, am, zo, omp, q</td>
<td></td>
</tr>
<tr>
<td>Capatana</td>
<td>S1-4 zo eclogite</td>
<td>grt–omp–zo–q–rt–op</td>
<td>irregular in alm, grs</td>
<td>omp, rt, q</td>
<td></td>
</tr>
<tr>
<td>Capatana</td>
<td>S1-5 zo eclogite</td>
<td>grt–omp–zo–q–rt–op</td>
<td>irregular in alm, grs</td>
<td>omp, rt, q</td>
<td></td>
</tr>
<tr>
<td>Capatana</td>
<td>S1-6 czo eclogite</td>
<td>grt–omp–czo–q–rt–op</td>
<td>irregular in alm, grs</td>
<td>omp, rt, czo, q</td>
<td></td>
</tr>
<tr>
<td><strong>Lotru</strong></td>
<td>Paltinis</td>
<td>L1 eclogite</td>
<td>grt–omp–rt–ilm</td>
<td>slight ↑grs</td>
<td>pl, am, ep, cpx</td>
</tr>
<tr>
<td>Paltinis</td>
<td>L2 eclogite</td>
<td>grt–omp–rt–ilm</td>
<td>negligible</td>
<td>am, cpx</td>
<td></td>
</tr>
<tr>
<td>Paltinis</td>
<td>L3 eclogite</td>
<td>grt–omp–rt–ilm</td>
<td>negligible</td>
<td>am, cpx, rt, ilm</td>
<td></td>
</tr>
<tr>
<td>Paltinis</td>
<td>L4 grt amphibolite</td>
<td>grt–am–pl–rt–op</td>
<td>negligible</td>
<td>zo, am</td>
<td></td>
</tr>
<tr>
<td>Paltinis</td>
<td>L5 grt peridotite</td>
<td>ol–opx–gurt</td>
<td>intergrain variation</td>
<td>spl, crn</td>
<td></td>
</tr>
<tr>
<td>Deluselu V</td>
<td>L7 eclogite</td>
<td>grt–omp–rt–op</td>
<td>slight intergrain var.</td>
<td>omp, rt</td>
<td></td>
</tr>
<tr>
<td>Deluselu V</td>
<td>L8 czo eclogite</td>
<td>grt–omp–czo–rt–op</td>
<td>irregular</td>
<td>zo, am, omp, rt</td>
<td></td>
</tr>
<tr>
<td><strong>Kumpana</strong></td>
<td>Topolog</td>
<td>C1 ky eclogite</td>
<td>grt–omp–ky–q–rt</td>
<td>negligible</td>
<td>am, kyb, omp, q</td>
</tr>
<tr>
<td>Topolog</td>
<td>C2 zo eclogite</td>
<td>grt–omp–zo–q–rt–ilm</td>
<td>sector</td>
<td>omp, rt, q</td>
<td></td>
</tr>
<tr>
<td>Cugir Valley</td>
<td>C3 bt grt amphibolite</td>
<td>grt–am–pl–bt–q–rt–ilm</td>
<td>negligible</td>
<td>chl, am, rt, q</td>
<td></td>
</tr>
<tr>
<td><strong>Bughea</strong></td>
<td>Danis</td>
<td>B1 zo–phn eclogite</td>
<td>grt–omp–zo–phn–q–rt</td>
<td>prograde</td>
<td>am, pg, zo, omp, phn</td>
</tr>
<tr>
<td>Bughita</td>
<td>B4 metagranite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bughita</td>
<td>B5 metagranite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Targului</td>
<td>B6 zo–phn eclogite</td>
<td>grt–omp–zo–phn–q–rt</td>
<td>sector</td>
<td>am, rt, q</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: alm, almandine; am, amphibole; bt, biotite; cpx, low-Na clinopyroxene; crn, corundum; ep, epidote; grs, grossular; grt, garnet; ilm, ilmenite; ky, kyanite; omp, omphacite; op, opaque mineral; pg, paragonite; phl, phlogopite; phn, phengite; pl, plagioclase; prp, pyrope; q, quartz; rt, rutile; spl, spinel; sps, spessartine; sympl, symplectite after omphacite; ttn, titanite; zo, zoisite. ↑, increase; ↓, decrease.

* Pre-HP stage inclusions in garnet designated by italics.

b Abundant fine needles of kyanite in garnet.
alogical features of the Foltea garnet peridotite are identical to those of high-temperature Mg–Cr garnet peridotites in Eurasian HP/UHP terranes elsewhere (Medaris, 1999). In contrast, garnet peridotite at Paltinis has formed from plagioclase peridotite that constitutes part of a layered metabasic–ultrabasic igneous complex (Maruntiu et al., 1998). Concomitant with transformation of gabbro to eclogite was the growth in peridotite of thin garnet and orthopyroxene reaction rims at the contacts between olivine and preexisting plagioclase (L5, Fig. 3), clearly establishing an early, low-pressure stage in the $P$–$T$–$t$ evolution of this particular garnet peridotite. Lenses of peridotite, which are scattered through the Sebes 1 unit, are also thought to have contained garnet, based on the presence of amphibole or chlorite pseudomorphs, but these peridotites are so extensively retrograded that they have not been investigated here.

Decameter-sized boudins of massive metagranite (sensu lato) occur in the Bughea complex, and the
analyzed samples were collected from the Bughita Albestilor Valley. Although the igneous texture of the metagranite is preserved on a hand specimen scale, microscopic examination reveals the growth of garnet at the boundaries of relict igneous biotite and opaques, the presence of phengite in biotite, and the replacement of feldspar by extremely fine-grained zoisite and kyanite (B4, Fig. 3).

Fig. 3. Photomicrographs (plane polarized light) of representative high-pressure rocks from the Lotru unit and Bughea complex. L3, eclogite, Paltinis, Lotru: peak assemblage of garnet (g), omphacite (o), and rutile (r), with retrograde amphibole (a) and clino.pyroxene–plagioclase symplectite (s) after omphacite. L5, garnet peridotite, Paltinis, Lotru: orthopyroxene (opx) and garnet (g) reaction products at the boundary of olivine (ol), partly serpentinized (srp), and former plagioclase, now consisting of amphibole, zoisite, and chlorite (a + z + chl); orthopyroxene and garnet are separated by an intergrowth of amphibole and spinel (a + spl). B6, zoisite–phengite eclogite, Tirgului, Bughea complex: fine-grained assemblage of garnet (g), omphacite (o), zoisite (z), phengite (phn), and sodic–calcic amphibole (a). B4, metagranite, Bughita, Bughea complex: garnet (g) growth at the boundary of relict biotite (b) and opaques with former feldspar (f), now replaced by extremely fine-grained zoisite and kyanite; note phengite (phn) grains within biotite.

4. Rock chemistry

4.1. Major elements

Major element compositions for 30 samples of peridotite, eclogite, granulite, amphibolite, and metagranite were determined by standard X-ray fluorescence techniques at the XRAL Laboratory, Ontario
ARTICLE IN PRESS

The two metagranites, samples B4 and B5 from the Bughea complex, are peraluminous adamellites, containing 4.7% and 8.6% normative c, and norma-

Fig. 4. Selected Harker diagrams for South Carpathian high-pressure metamorphic basic and intermediate rocks, illustrating some of their important geochemical characteristics (peridotite and metagranite are not included because of scale considerations). All data are plotted on an anhydrous basis, normalized to 100%; symbols as in Fig. 5. Alkaline and subalkaline fields from Irvine and Baragar (1971); tholeiitic and calc-alkaline fields from Miyashiro (1975); basic and intermediate fields by convention.
4.2. Nd isotopes and geochronology

4.2.1. Methods

Four high-pressure rocks from the South Carpathians, including two eclogites, one garnet amphibolite, and one garnet peridotite, were analyzed for Sm–Nd mineral–whole-rock geochronology. Fresh whole-rock samples (typically 100–500 g) were crushed in a jaw crusher to about 1/3 of their average grain size. Sample segments with visible alteration products were discarded. The samples were then homogenized and split, roughly two-thirds for mineral separation, and a third for whole-rock analysis. Both splits were initially washed in deionized water and then acid leached for 25–30 min in warm 1 N distilled HCl, while in an ultrasonic bath. The whole-rock samples were then ground to a fine powder using a shatterbox prior to their dissolution. The split for mineral analyses remained relatively coarse throughout the separation procedure, although for some samples rich in composite grains, a few additional grinding steps were necessary. Separation of minerals was accomplished by a Franz magnetic separator and handpicking in alcohol under a binocular microscope. The mineral separation procedure resulted in two fractions for each mineral:

(1) ultrapure mineral separates, containing translucent grains with no stains or visible inclusions and (2) lower purity separates, which contained occasional kelyphitic rims or common inclusions of other minerals.

The second fraction was not used further in analyses. To eliminate any grain-boundary alteration effects, the handpicked mineral separates were leached again in 2.5 N distilled HCl. The samples were then ultrasonically cleaned, rinsed multiple times with ultrapure water and dried in methanol.

The samples were spiked with mixed $^{147}$Sm–$^{150}$Nd tracers. Dissolution of the spiked samples for isotopic analyses was performed in screw-cap Teflon beakers using HF–HNO$_3$ (on hot plates) and HF–HClO$_3$ mixtures (in open beakers at room temperature). A few garnet separates were subjected to several, up to three dissolution steps, before becoming residue-free. The samples were taken in 1 N HCl and any undissolved residue was attacked in the same way. Separation of the bulk of the REE was achieved via HCl elution in cation columns. Separation of Sm and Nd was carried out using an LNSpec$^®$ resin. The highest procedural blanks measured during the course of this study were: 5 pg Sm and 18 pg Nd.

Isotopic analyses for Nd, as well as isotope dilution analyses of Sm, and Nd were performed at the University of Arizona using a VG 354 multiple col-

Fig. 5. AFM diagram for South Carpathian high-pressure rocks. All Fe is taken as FeO; tholeiitic and calc-alkaline fields from Irvine and Baragar (1971).

Fig. 6. Correlation of eclogite mineral assemblage and major element chemical composition, in terms of wt.% CaO and molar MgO/(MgO+FeO). Sample S1-3 is a zoisite–kyanite eclogite. Duplicate sample numbers in upright and italicized type indicate analyses of samples from the same outcrop.
lector mass spectrometer. The filament loading and mass spectrometric analysis procedures were similar to the ones previously described by Patchett and Ruiz (1987). The Nd isotopic ratios were normalized to 146Nd/144Nd = 0.7219. Estimated analytical uncertainties are: 147Sm/144Nd = 0.8%, and 143Nd/144Nd = 0.002%. External reproducibility, based on the range of multiple runs of standard La Jolla Nd is estimated to be \( \pm 0.00001 \). Replicate analyses of two samples analyzed in this study (garnet and clinopyroxene from samples L3 and L1) indicate similar reproducibility. The grand means of isotopic ratios were corrected by an off-line manipulation program, which adjusts for the spike contributions to both the fractionation correction and each ratio, and performs isotope dilution calculations.

### 4.2.2. Results

Four mineral and whole rock Sm–Nd isochron ages were determined (Table 2, Fig. 7), one on a garnet peridotite, two on eclogites and one on a biotite–garnet amphibolite. Eclogite L1 of the Lotru unit near Paltinis yielded a garnet–whole-rock age of 341.4 ± 8.2 (2\( \sigma \)) Ma. Eclogite L3 from the same unit

![Fig. 7. Sm–Nd mineral–whole-rock isochron diagram for samples S3-2 (garnet peridotite, Foltea), L1 (eclogite, Paltinis), L3 (eclogite, Paltinis), and C3 (garnet amphibolite, Cugir Valley). Isochron ages were calculated using the ISOPLOT program of Ludwig (1991).](image-url)
yielded a four-point isochron age of 343.6 ± 6.6 Ma, identical within errors with L1. The whole-rock Sm/Nd is lower than that of each of the individual analyzed phases in eclogite L3, probably because of the presence of apatite which contributes significantly to the REE budget of this sample. Amphibolite C3 from Cugir Valley (Cumpana unit) yielded a garnet–whole-rock age of 358 ± 10 Ma, within error of eclogites L1 and L3. These Sm–Nd ages for eclogite and garnet amphibolite are believed to represent the high-pressure metamorphic age within 3–8 My, based on the observed grain sizes in these rocks and assuming a cooling rate of 10 °C/My (following Ganguly et al., 1998). Compared to the previous rocks, the Foltea garnet peridotite (Sebes unit) has a younger garnet–clinopyroxene–whole-rock age of 315.5 ± 4.2 Ma.

5. Mineral chemistry

Mineral compositions were determined by means of a Cameca SX50 electron microprobe, using an accelerating voltage of 15 kV, a beam current of 20 nA, a suite of analyzed natural minerals as standards, and the ϕ(ρz) data reduction program (Armstrong, 1988). Based on replicate analyses, major element abundances are estimated to be precise within ±3% and minor element abundances within ±10%. Analyses used in thermobarometric calculations are available from the first author upon request. Ferric/ferrous ratios for garnet and clinopyroxene were calculated from the means of numerous spot analyses by stoichiometry, following the method of Ryburn et al. (1976), and for amphibole, by the method of Robinson et al. (1982), taking total cations to be 13, exclusive of K, Na, and Ca.

5.1. Garnet

Garnet compositions for all samples are plotted in Fig. 8, arranged by tectonostratigraphic unit and locality. Garnet exhibits a wide range in composition among the analyzed samples and encompasses the entire spectrum of garnet compositions from type A, B, and C eclogites, as defined by Coleman et al. (1965). Such a wide range in garnet composition reflects in large part the predominant influence of rock chemistry on garnet composition in the investigated eclogites, which typically contain low variance mineral assemblages. For example, the most pyrope-rich garnet among the analyzed samples occurs in the Foltea Mg–Cr peridotite (S3-1), and garnet in eclogite, amphibolite, and peridotite from the Lotru Paltinis suite (L1-5) spans a wide range in composition.

Garnet consists essentially of almandine–pyrope–grossular solid solutions, with spessartine component always being less than 4 mol% and generally, less than 1 mol%. Except where destroyed by growth of kelyphite, retrograde compositional zoning commonly occurs within ~50 μm of garnet margins, due to arrested Fe–Mg exchange during cooling. Although...
the interiors of some garnet grains are compositionally homogeneous, other grains show a variety of compositional zoning patterns, including irregular, prograde, and sector types (summarized in Table 1). Prograde compositional zoning, which is best preserved in garnet grains in the Bughea complex (sample B3, Fig. 9), exhibits a core to rim decrease in Mn and increase in Mg, little change in Fe, and decrease in Ca at the rim. Sector zoned garnet has been found in two eclogite samples (sample C2, zoisite eclogite, Topolog locality, Cumpana unit, and sample B6, zoisite–phengite eclogite, Raul Targuul locality, Bughea complex). The sector zoning, which is developed in an intermediate domain between an indistinct core and outer rim, is due to heterogeneous distribution of Mg and Fe on the \{110\} faces of garnet (sample B6, Fig. 9). Mn shows less pronounced sector variation, and Ca is uniform in the intermediate domain. The rim of the grain is characterized by an increase in Mg, slight increase in Mn, and decreases in Fe and Ca. Such sector zoning, although rare in metamorphic garnet, has been described by Shirahata and Hirajima (1995) for garnet at several localities in the Sanbagawa schist.

5.2. Clinopyroxene

The interiors of clinopyroxene grains in eclogite are relatively homogeneous, but Al and Na decrease and Mg, Fe, and Ca increase at grain boundaries and in the vicinity of symplectite, in response to partial reequilibration during decompression. Clinopyroxene compositions, in terms of jadeite, diopside + hedenbergite + Ca-tschermakite, and acmite, are plotted in Fig. 10 according to tectonostratigraphic unit and locality. The maximum jadeite content of pyroxene in eclogite is largely determined by rock chemistry, stable plagioclase being absent from the high-pressure assemblage, and although omphacite occurs in most of the analyzed samples, sodic augite is the stable pyroxene in less sodic eclogites, such as S1-1, S1-2,

![Fig. 9. X-ray maps of garnet in eclogite from the Bughea complex; light shades represent higher elemental concentrations and dark shades, lower concentrations. B3, kyanite–phengite–paragonite eclogite, Bughta: prograde compositional zoning patterns in two amalgamated garnet grains (diameter of garnet is 2 mm); B6, zoisite–phengite eclogite, Targuul: strong sector zoning in Mg and Fe, faint sector zoning in Mn, and concentric zoning in Ca (diameter of garnet is 1 mm).]
L7, and L8. Sodic augite occurs in Mg-rich and Na-poor eclogites elsewhere, e.g. the Silberbach eclogite in the Münchberg Massif, which is thought to be cumulate in origin (Stosch and Lugmair, 1990). Mineralogical evidence for a prograde history is provided by clinopyroxene in the Lotru Paltinis eclogite (Fig. 10, L1,2,3), in which sodic augite occurs as inclusions in garnet, and omphacite, in the matrix. Clinopyroxene in symplectite, which occurs to some degree in all eclogite samples, ranges in composition from sodic augite to almost Na-free clinopyroxene.

Clinopyroxene in garnet granulite S2-1 occurs with plagioclase and contains almost no jadeite component (Fig. 10), despite a calculated pressure of 11.7 kbar (see below). Clinopyroxene in the Foltea garnet peridotite (samples S3-1 and S3-2, not figured), is Cr-diopside, containing 0.78–0.92 wt.% Cr₂O₃ and 10 mol% jadeite.

5.3. Amphibole

Amphibole is a widespread and abundant mineral in high-pressure metabasic rocks in the South Carpathians, deserving of a detailed treatment that is beyond the scope of the present investigation. Amphibole is an essential constituent in amphibolite and granulite (Fig. 2), and it occurs in eclogite as inclusions in garnet, matrix grains in some samples, and a retrograde product, commonly in poikilitic or kelyphitic textures. The compositions of predominant amphibole in the analyzed samples are shown in Fig. 11 (modified after Leake, 1997), in which Na occupancy in the B-site is plotted against Si per formula unit, and level of Na+K occupancy in the A-site is indicated by open (<0.5) and closed (>0.5) symbols.

Amphibole in granulite, amphibolite, and most eclogite is calcic, but sodic–calcic amphibole is characteristic of eclogite samples S1-5 (Sebes 1, Capatană), C1 (Cumpa, Topolog), and B1, B2, and B3 (Bughea complex). Calcic amphibole in most eclogite samples appears to be retrograde, based on its interstitial occurrence and kelyphitic growth around garnet. In contrast, sodic–calcic amphibole is in apparent textural equilibrium with garnet and omphacite. Most amphibole contains more than six atoms of Si per formula unit, but amphibole inclusions in garnet in samples S1-3, S2-2, L2, and L3 are unusually aluminous, containing less than six atoms of Si. Within several samples, an increase in Si appears to be correlated with a decrease in level of Na+K in the A-site (Fig. 11).

6. Thermobarometry

6.1. Methods

In calculating temperatures and pressures for poly- metamorphic rocks that commonly contain zoned minerals, the problem arises as to what parts of mineral grains, if any, are in equilibrium and suitable for $P-T$ evaluation. For eclogite that contains prograde-zoned garnet, maximum $P-T$ conditions were
obtained from the most pyrope-rich part of the zoned garnet, combined with the most jadeite-rich core of adjacent clinopyroxene, following the suggestion of Spear (1991). An analogous approach was taken for other analyzed high-pressure lithologies, utilizing the most pyrope-rich part of garnet, combined with domains of pertinent coexisting minerals that were judged to be in equilibrium, based on petrographic observation, backscattered electron imaging, numerous spot analyses of several grains in each sample, and selected line traverses and X-ray mapping. An additional problem in Fe–Mg exchange thermometry is estimation of the oxidation state of iron in ferromagnesian phases. As described in the section on mineral chemistry, ferric/ferrous ratios were calculated from charge-balance considerations for garnet, clinopyroxene, and amphibole. Although such estimates of ferric/ferrous ratios have inherent difficulties (Sobolev et al., 1999), the relative differences in values among samples are thought to be significant, because the same set of standards and operating conditions were used throughout the collection of mineral compositional data.

For eclogite, metamorphic conditions were calculated from calibrations of the following equilibria:

\[
\text{Prp} + 3\text{Di} = \text{Alm} + 3\text{Hd}
\]
(Powell, 1985)

\[
\text{Jd} + \text{Qtz} = \text{Ab}
\]
(Gasparik, 1985; Brown et al., 1989; Holland, 1990)

\[
\text{Prp} + 2\text{Grs} = 6\text{Di} + 3\text{Phn}
\]
(Waters and Martin, 1993; Searle et al., 1994)

\[
\text{Pg} = \text{Jd} + \text{Ky} + H_2O
\]
(Brown et al., 1989; Holland, 1990)

\[
12\text{Zo} + 15\text{Di} = 13\text{Grs} + 5\text{Prp} + 12\text{Qtz} + 6H_2O
\]
(Brown et al., 1989)

Solutions to combinations of the various equilibria were obtained by iteration or application of the GEOCALC program (Berman, 1988; Brown et al., 1989). Regardless of whether the Gasparik (1985) or Holland (1990) calibration was used for equilibrium (2), com-

Fig. 11. Summary of amphibole compositions in South Carpathian high-pressure rocks. Plot based on the IMA classification scheme (Leake, 1997); filled circles indicate (Na + K)A-site ≥ 0.5, open circles, (Na + K)A-site ≤ 0.5. Abbreviations: rich, richterite; kat, kataphorite; tar, taramite; ed, edenite; parg, pargasite; win, winchite; bar, barroisite; tr, tremolite; hb, hornblende; tsch, tschermakite.
parable results were obtained. Because stable plagioclase is absent from the eclogite assemblages, the resulting pressures and, to a lesser degree, temperatures are minimum values, although the presence of stable phengite or paragonite in some samples of eclogite allows a definitive $P$–$T$ value to be established. For samples containing stable paragonite or zoisite, estimates for $H_2O$ activity may be obtained from some combination of equilibria (4) and (5) with equilibria (1)–(3), depending on the specific mineral assemblage.

Conditions for garnet granulite were determined from Fe–Mg exchange between clinopyroxene and garnet, equilibrium (1), and the following:

$$3\text{Fe} – \text{Pr}g + 4\text{Pr}p = 3\text{Pr}g + 4\text{Alm}$$  (Graham and Powell, 1984)

$$3\text{Di} + 3\text{An} = 2\text{Gr}s + \text{Pr}p + 3\text{Qtz}$$  (Brown et al., 1989)

The combination of results from equilibria (1) and (6) with equilibrium (7) yields a specific temperature and pressure, and application of equilibrium (8), in the absence of rutile, provides a maximum pressure.

Equilibration conditions for garnet amphibolite were obtained from Fe–Mg exchange between amphibole and garnet, equilibrium (6), and two end-member equilibria (Mg and Fe) for the assemblage, plagioclase–amphibole–garnet–quartz:

$$6\text{An} + 3\text{Tr} = 2\text{Gr}s + \text{Pr}p + 3\text{Tsch} + 6\text{Qtz}$$  (Kohn and Spear, 1990)

The preferred method of approximating maximum temperatures for garnet peridotite is based on the compositions of coexisting garnet, which is a slowly diffusing phase, and matrix olivine, which consti-

### Table 3: Temperature–pressure conditions for South Carpathian high-pressure rocks

<table>
<thead>
<tr>
<th>Unit and locality</th>
<th>Sample</th>
<th>Lithology</th>
<th>$T$ (°C)</th>
<th>$P$ (kbar)</th>
<th>$a(H_2O)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sebes 3</strong></td>
<td>Foltea S3-1</td>
<td>grt peridotite</td>
<td>1297$^1$, 29.0$^2$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Foltea S3-2</td>
<td>grt peridotite</td>
<td>1149$^1$, 25.8$^2$</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Sebes 2</strong></td>
<td>S2-1</td>
<td>grt granulite</td>
<td>703$^3$, 11.7$^4$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Valley</td>
<td>S2-2</td>
<td>grt amphibolite</td>
<td>909$^5$, 14.5$^6$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Sebes 1</strong></td>
<td>S1-1</td>
<td>ky eclogite</td>
<td>$\geq 546^3$, 11.6$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mehedinti S1-2</td>
<td>ky–phn</td>
<td>eclogite</td>
<td>604$^3$, 11.8$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mehedinti S1-3</td>
<td>zo–ky</td>
<td>eclogite</td>
<td>$\geq 569^3$, 13.8$^7$</td>
<td>$\geq 0.15^{10}$</td>
<td>–</td>
</tr>
<tr>
<td>Capatana S1-4</td>
<td>zo eclogite</td>
<td>–</td>
<td>$\geq 665^3$, 15.2$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Capatana S1-5</td>
<td>zo eclogite</td>
<td>–</td>
<td>$\geq 647^3$, 14.9$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Capatana S1-6</td>
<td>czo eclogite</td>
<td>–</td>
<td>$\geq 621^3$, 14.1$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Lotru</strong></td>
<td>L1</td>
<td>eclogite</td>
<td>$\geq 662^3$, 12.3$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Paltinis L2</td>
<td>eclogite</td>
<td>–</td>
<td>$\geq 685^3$, 13.4$^3$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Paltinis L3</td>
<td>eclogite</td>
<td>–</td>
<td>$\geq 671^3$, 13.1$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Paltinis L4</td>
<td>ggt amphibolite</td>
<td>–</td>
<td>710$^3$, 13.4$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Paltinis L5</td>
<td>ggt peridotite</td>
<td>–</td>
<td>559$^1$, 16.1$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Deluselu V. L7</td>
<td>eclogite</td>
<td>–</td>
<td>$\geq 652^3$, 12.5$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Deluselu V. L8</td>
<td>czo eclogite</td>
<td>–</td>
<td>$\geq 694^3$, 12.4$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Cumpana</strong></td>
<td>C1</td>
<td>ky eclogite</td>
<td>$\geq 616^3$, 14.5$^7$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Topolog C2</td>
<td>zo eclogite</td>
<td>–</td>
<td>$\geq 619^3$, 14.3$^7$</td>
<td>$\geq 0.3^{10}$</td>
<td>–</td>
</tr>
<tr>
<td>Cugir C3</td>
<td>bt ggt</td>
<td>–</td>
<td>710$^3$, 10.5$^6$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Valley</td>
<td>czo amphibolite</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Bughea</strong></td>
<td>B1</td>
<td>zo–phn</td>
<td>$\geq 686^3$, 15.5$^7$</td>
<td>$\sim 1.0^{10}$</td>
<td>–</td>
</tr>
<tr>
<td>Bughita B2</td>
<td>ky–phn–pg</td>
<td>eclogite</td>
<td>608$^3$, 22.3$^{11}$</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>Bughita B3</td>
<td>ky–phn–pg</td>
<td>eclogite</td>
<td>746$^3$, 19.0$^{11}$</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>Tirguhui B6</td>
<td>zo–phn</td>
<td>eclogite</td>
<td>$\geq 577^3$, 16.4$^7$</td>
<td>$\sim 0.35^{10}$</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes to Table 3:

Equilibria used in thermobarometric calculations: $^1$Fe–Mg exchange, ol–ggr (O’Neill and Wood, 1979; O’Neill, 1980); $^2$Al-in-opx (Brey and Köhler, 1990); $^3$Fe–Mg exchange, cpx–ggr (Powell, 1985); $^4$di + an = grs + prp + q (Brown et al., 1989); $^5$Fe–Mg exchange, hbl–ggr (Graham and Powell, 1984); $^6$an + tr = grs + prp + tsc + q (Kohn and Spear, 1990); $^7$a(Jd) in cpx (Gasparik, 1985); $^8$prp + grs = di + phn (Waters and Martin, 1993); $^9$Fe–Mg exchange, opx–ggr (Brey and Köhler, 1990); $^{10}$zo + di = grs + prp + q + V (Brown et al., 1989); $^{11}$pg = jd + ky + V (Brown et al., 1989).
tutes the bulk of the rock and whose composition is little changed by intergranular diffusion during cooling (Brenker and Brey, 1997), according to the equilibrium:

\[ \frac{1}{2}Fa + \frac{1}{3}Prp = \frac{1}{2}Fo + \frac{1}{3}Alm \]  

(O’Neill and Wood, 1979; O’Neill, 1980)

Pressure is then determined from the Al-in-orthopyroxene barometer:

\[ Prp = En + Tsch(opx) \]  

(Brey and Köhler, 1990)

An additional Fe–Mg exchange equilibrium:

\[ \frac{1}{2}Fs + \frac{1}{3}Prp = \frac{1}{2}En + \frac{1}{3}Alm \]  

(Brey and Köhler, 1990)

was utilized for the Lotru Paltinis garnet peridotite, in which grains of garnet are never in direct contact with olivine and orthopyroxene.

6.2. Results

South Carpathian eclogite belongs to the medium-temperature group (Carswell, 1990), and samples range in temperature from \( \sim 545 \) to \( 745 \) °C and in pressure from \( \sim 11.2 \) to \( 22.3 \) kbar (Table 3, Fig. 12), remembering, however, the caveat that the \( P–T \) determinations derived from the jadeite content of omphacite are only minima (note that the temperatures cited here are generally lower than those reported by Maruntiu et al., 1997, and Iancu et al., 1998, because their determinations apparently did not include a correction for ferric iron). Pressure estimates from equilibrium (4) for paragonite-bearing samples, B2 and B3, are significantly higher than those predicted by their omphacite compositions, 22.3 vs. 13.6 kbar and 19.0 vs. 16.2 kbar, respectively. Pressure estimates based on phengite composition are comparable to that based on jadeite content of pyroxene in sample S1-2 (11.2 vs. 10.8 kbar), higher in sample B6 (16.4 vs. 13.9 kbar), and appreciably lower in samples B2.
and B3, possibly due to retrograde re-equilibration of phengite in these two samples. Application of equilibrium (5) to three samples of zoisite eclogite (S1-3, C2, and B6) suggests that H₂O activity was substantially reduced at the eclogite stage, on the order of 0.15–0.35, although a fourth sample (B1) indicates an activity of ~1.0.

Despite the small number of analyzed samples, it appears that $P$–$T$ fields are relatively restricted at each specific locality, except for the Bughea complex (tectonic mélangé), and differ among the tectonostratigraphic units, as well as within some units, such as the Mehedinti and Capatan localities in Sebes 1 (Figs. 12 and 13). However, additional analyses are required to evaluate the possibility of regional trends in $P$ and $T$.

Pyroxene and amphibole equilibria applied to garnet granulite (S2-1) yield consistent results of 703 °C, 11.7 kbar and 714 °C, 11.4 kbar (Table 3, Fig. 12), and demonstrate the high-pressure nature of Sebes 2 granulite. The three analyzed samples of garnet amphibolite (S2-2, L4, and C3), each from a different tectonostratigraphic unit, also equilibrated at high pressure, from 10.5 to 14.5 kbar (Table 3, Fig. 12).

Extreme $P$–$T$ conditions (~1150–1300 °C, 25.8–29.0 kbar) are preserved in the Foltea garnet peridotite, Sebes 3 unit, but much lower $P$–$T$ conditions (~560–620 °C, 16.1–19.1 kbar) are recorded in the Paltinis garnet peridotite, Lotru unit. Such disparate conditions reflect the contrasting tectono-thermal regimes for the two types of peridotite, the Foltea body originating by the introduction of hot mantle into the Sebes 3 crustal sequence, and the Paltinis body representing part of a mafic–ultramafic complex that shared a prograde metamorphic history with associated Lotru crust.

7. Discussion

The Sm–Nd ages reported here for Sebes 3 garnet peridotite (316 ± 4 Ma), Lotru eclogite (341 ± 8 and 344 ± 7 Ma), and Cumpana garnet amphibolite (358 ± 10 Ma) firmly establish a Variscan age for high-pressure metamorphism of the pre-Alpine Gotic–Supragetic basement in the South Carpathians. Although the eclogite and amphibolite ages are indistinguishable within error, the peridotite age is signif-
icantly younger, raising the possibility that high-pressure metamorphism (or exhumation) was diachronous in different tectonostratigraphic units in the South Carpathians, as elsewhere in the European Variscides (Brueckner et al., 1991; Beard et al., 1995). Our newly determined Variscan metamorphic ages are consistent with three types of previously acquired geochronological data: (1) several $^{207}\text{Pb}/^{206}\text{Pb}$ analyses of zircon from synkinematic pegmatites in Getic basement yielded ages of 338–333 Ma, with no errors reported (Ledru et al., 1997), (2) Sm–Nd mineral ages of 358–323 Ma were determined for Cumpana amphibolites and gneisses (Dragusanu and Tanaka, 1999), and (3) ~ 320–295 Ma $^{40}\text{Ar}–^{39}\text{Ar}$ cooling ages for hornblende and muscovite were determined on samples from throughout the Getic and Supragetic basement nappes (Dallmeyer et al., 1998). The Sm–Nd data presented here and in Dragusanu and Tanaka (1999), when compared to the limited U–Pb zircon geochronology of Getic basement pegmatites (Ledru et al., 1997), suggest that partial melting and production of pervasive pegmatites and migmatites within the Getic basement (Balintoni, 1975) took place synchronously with, or shortly following, the Variscan peak metamorphism. The Sm–Nd results combined with published $^{40}\text{Ar}–^{39}\text{Ar}$ ages suggest initial (i.e. high temperature) cooling rates of about 10 ± 5 °C/My, based on estimated closure temperatures of ~ 650 °C for Sm–Nd in garnet (following Ganguly et al., 1998) and 500 °C for Ar diffusion in hornblende (Dallmeyer et al., 1998). It has been suggested that the cooling/unroofing of the basement rocks and deposition of unmetamorphosed Carboniferous–Permian sediments took place during an episode of continental extension between 320 and 300 Ma (Dallmeyer et al., 1998). Such a scenario is consistent with the hypothesis that the Variscan orogen of Europe has collapsed in its late stages, leading to the formation of numerous continental extensional basins (Menard and Molnar, 1988).

We interpret the Sm–Nd age of the high-temperature Foltea garnet peridotite to represent the time of its tectonic emplacement into the crust, when it cooled through an estimated garnet Sm–Nd closure temperature of ~ 850 °C, assuming a cooling rate of 100 °C/My (Ganguly et al., 1998). Interestingly, emplacement of the hot, asthenosphere-derived Foltea garnet peridotite in the Getic basement took place during extension towards the end of the orogeny, subsequent to the peak of Variscan high-pressure metamorphism and migmatization. The emplacement of the Foltea peridotite could possibly be a result of late orogenic delamination of mantle lithosphere in the area, as postulated for similar high-temperature garnet peridotites in the Bohemian Massif (Medaris et al., 1990; 1998).

Further detailed investigation is needed to verify the apparent differences in “peak” eclogite facies conditions among different tectonostratigraphic units (Fig. 13) and to establish $P–T–t$ paths for high-pressure lithologic associations at individual localities. The Paltinis metabasic–ultrabasic complex raises the intriguing possibility that garnet peridotite (L5), eclogite (L1–3), and garnet amphibolite (L4) have captured $P–T$ conditions experienced by the complex at various times along a clockwise metamorphic path (Fig. 12), although the differences in $P–T$ estimates among the three rock types might also be due to disequilibrium in the garnet peridotite (note the distribution of orthopyroxene and garnet illustrated in Fig. 3) or to inherent differences in $P–T$ estimates derived from different equilibria. Another interesting result from our $P–T$ estimates is that samples of garnet amphibolite in the Lotru (L4) and Cumpana (C3) units yield higher temperatures than do eclogites in the same units, and garnet amphibolite and garnet granulite in the Sebes 2 unit give elevated temperatures of ~ 910 and 710 °C, respectively (Fig. 13). Such a temperature distribution might signify post-eclogite stage heating, perhaps due to thermal relaxation of crustal rocks that were thickened by nappe stacking, or the apparent temperature pattern may again be due to differences among different geothermometers. High temperatures in the Sebes 2 and 3 units may originate from the introduction of high-temperature peridotite masses, whose emplacement may be related to Late Carboniferous extension.

The existence of relatively low H$_2$O activity in some samples of eclogite, for which there is limited evidence from several zoisite eclogites, is consistent with the apparent absence of amphibole and paragonite, whose stability fields are restricted at reduced H$_2$O activity, from the peak mineral assemblages in most eclogite samples.

The Sebes 2 and 3 units are noteworthy for the presence of high-temperature garnet peridotite, the
occurrence of leptynite–amphibolite, the development of elevated temperatures in granulite and amphibolite, and the rarity of eclogite, although textures in granulite and amphibolite suggest that they formed from preexisting eclogite. Such features closely resemble those of the Gfo¨hl Nappe in the Bohemian Massif, in which post-eclogite, high-temperature recrystallization has largely obliterated evidence for the prior existence of eclogite (Medaris et al., 1998). The Sebes 2 and 3 units are the uppermost tectonic units in the South Carpathians, as is the Gfo¨hl Nappe in the Bohemian Massif, and the likely correlation of these similar tectonostratigraphic entities provides a plausible link between the Variscan basement of the South Carpathians and that of central Europe.

8. Conclusions

High-pressure metamorphic rocks, including garnet peridotite, eclogite, garnet granulite, and garnet amphibolite are important constituents in the Sebes, Lotru, and Cumpana units and in the Bughea complex (tectonic mélange) of the pre-Alpine nappe stack of the Getic–Supragetic basement in the South Carpathians. Sm–Nd mineral–whole-rock isochrons for garnet peridotite (316 ± 4 Ma), eclogite (341 ± 8 and 344 ± 7 Ma), and garnet amphibolite (358 ± 10 Ma) demonstrate a Variscan age for high-pressure metamorphism, which is consistent with deposition of detritus from the high-pressure terranes in Westphalian to Permian sedimentary basins.

$P$–$T$ conditions for eclogite are in the range, 545–745 °C and 11.2–22.3 kbar, which may be attributed to subduction and continental collision in Carboniferous (pre-Westphalian) time. A widespread, post-eclogite recrystallization at possibly higher temperatures and the emplacement of high-temperature peridotite in Sebes 2 and 3, the uppermost structural units in the South Carpathians, may be related to late Variscan extensional processes.

In summary, the Variscan evolution of the pre-Mesozoic Getic–Supragetic basement in the South Carpathians is similar to that in other segments of the European Variscides, including widespread high-pressure metamorphism, whose $P$–$T$–$t$ signatures are specific to individual tectonostratigraphic units, the presence of diverse types of garnet peridotite, diachronous subduction and accretion, nappe assembly in pre-Westphalian time due to collision of Laurussia, Gondwana, and amalgamated terranes, and finally, rapid exhumation, cooling, and deposition of eroded debris in Westphalian to Permian sedimentary basins.

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