

Clockwise exhumation path of granulitized eclogites from the Ama Drime range (Eastern Himalayas)

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ABSTRACT The metamorphic evolution of a granulitized eclogite from the Phung Chu Valley (Eastern Himalaya) was reconstructed combining microstructural observations, conventional thermobarometry and quantitative pseudosection analysis. The granulitized eclogite consists of clinopyroxene, plagioclase, garnet, brown amphibole, and minor orthopyroxene, biotite, ilmenite and quartz. On the basis of microstructural observations and mineral relationships, four metamorphic stages and related mineral assemblages have been recognized: (i) M1 eclogite-facies assemblage, consisting of garnet, omphacite (now replaced by a clinopyroxene + plagioclase symplectite) and phengite (replaced by biotite + plagioclase symplectite); (ii) M2 granulite-facies assemblage, represented by clinopyroxene, orthopyroxene, garnet, plagioclase and accessory ilmenite; (iii) M3 plagioclase + orthopyroxene corona developed around garnet, and (iv) M4 brown amphibole + plagioclase assemblage in the rock matrix. Because of the nearly complete lack of eclogitic mineral relics, M1 conditions can be only loosely constrained at >1.5 GPa and >580 °C. In contrast, assemblage M2 tightly constrains the peak granulitic stage at 0.8–1.0 GPa and >750 °C. The second granulitic assemblage M3, represented by the plagioclase + orthopyroxene corona, formed at lower pressures (~0.4 GPa and ~750 °C). During the subsequent exhumation, the granulitized eclogite experienced significant cooling to nearly 700 °C, marked by the appearance of brown amphibole and plagioclase (M4) in the rock matrix. U–Pb SHRIMP analyses on low-U rims of zircon from an eclogite of the same locality suggest an age of 13–14 Ma for the M3 stage. The resulting decompressional clockwise *P–T* path of the Ama Drime eclogite is characterized by nearly isothermal decompression from >1.5 GPa to ~0.4 GPa, followed by nearly isobaric cooling from ~775 °C to ~710 °C. Modelling of phase equilibria by a calculated petrogenetic grid and conventional thermobarometry on a biotite–garnet–sillimanite metapelite hosted in the country rock granitic orthogneiss extends the inferred *P–T* trajectory down to ~630 °C and ~0.3 GPa.

Key words: Ama Drime Range; eastern Himalaya; granulitized eclogite; *P–T* path; pseudosection.

INTRODUCTION

The Himalayas are well known as the type orogen for inverted metamorphism, i.e. Barrovian metamorphism increasing in grade from structurally and topographically lower levels towards higher levels of the orogen, and over the years many investigations have been devoted to this feature of Himalayan geology (Gansser, 1964; Le Fort, 1975; Hodges, 2000). Only in the last 15 years, however, have geologists and field petrologists discovered that mineral assemblages of high pressure and even ultra-high pressure have been preserved under the veil of the Barrovian metamorphism. Eclogites, in particular, first discovered by Berthelsen (1953) as boudinaged dykes in the granitic orthogneiss of the Tso Moriri dome, eastern Ladakh (Fig. 1), were found at the end of the 1980s in the Kaghan Valley, NE Pakistan (Spencer *et al.*, 1990; Pognante & Spencer, 1991) and of the adjoining

Neelum Valley (Fontan *et al.*, 2000) (Fig. 1), whereas granulitized and amphibolitized eclogites were discovered in the Eastern Himalaya (Lombardo *et al.*, 1998; Parkinson & Kohn, 2002).

Recent investigations of the Tso Moriri rocks have shown that the eclogites are glaucophane- and coesite-bearing (De Sigoyer *et al.*, 1997; Mukherjee & Sachan, 2001), and occur both within the Cambro-Ordovician metagranitic basement and in the Permian metasedimentary cover. Petrological and thermobarometrical evidence indicates that the Tso Moriri eclogites record a ultrahigh-pressure stage at >3.9 GPa and >750 °C (Mukherjee *et al.*, 2003), whereas conventional geothermobarometry, stability fields of minerals and THERMOCALC *P–T* estimates indicate 2.0 GPa and 550 °C for the jadeite + chloritoid + paragonite + garnet peak assemblage in Fe-rich metapelites associated with the eclogites (Guillot *et al.*, 1997). A c. 55 Ma age for the eclogitization has been obtained

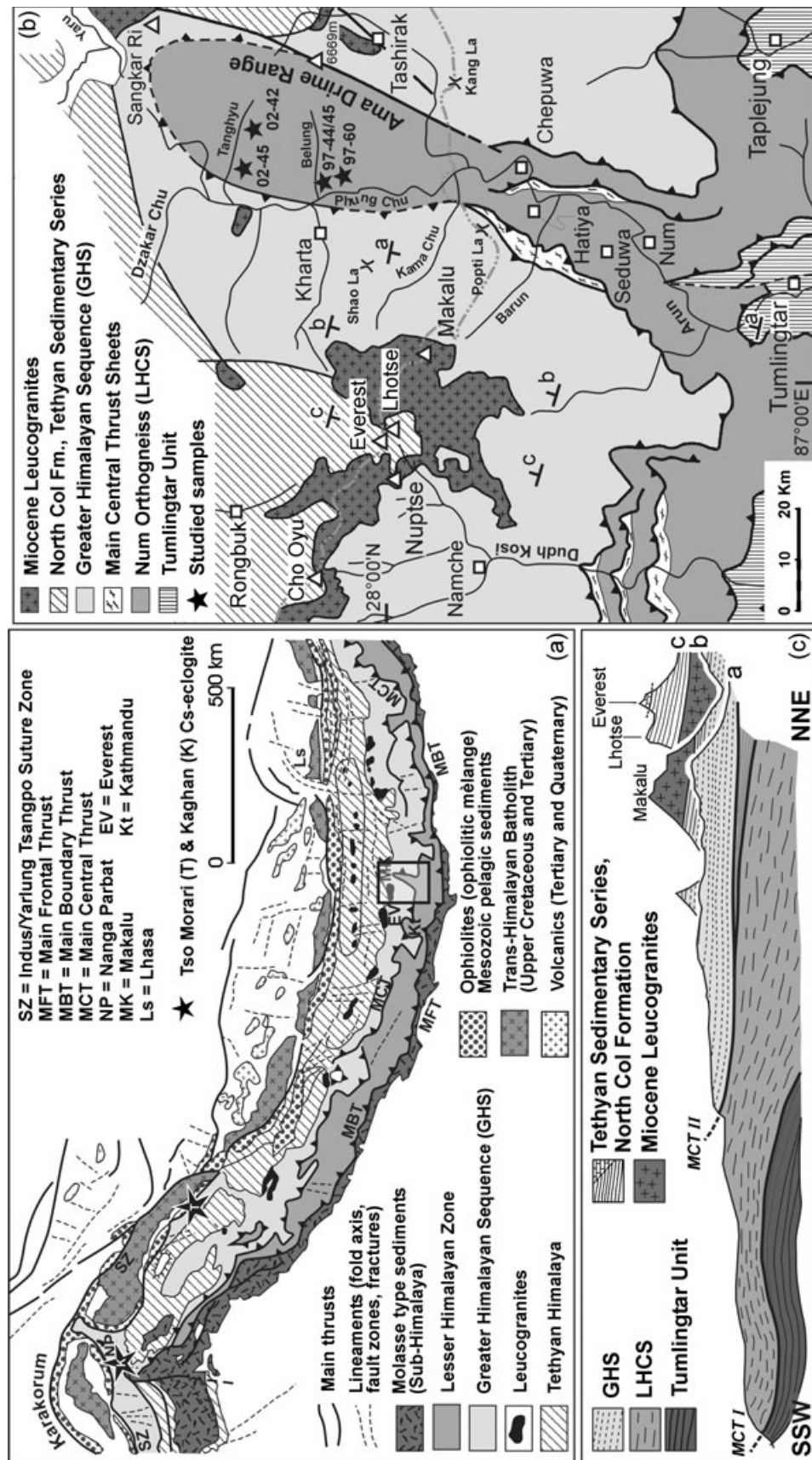


Fig. 1. (a) Geological sketch map of the Himalaya and southern Tibetan Plateau (from Dietrich & Gansser, 1981). The Ama Drime Range and Kharta region are shown in the box. (b) Geological sketch map of the Kharta region and upper to middle Arun (Phung Chu) drainage. The map was compiled from the maps of Yin & Kuo (1978), Burg (1983), Bureau of Geology and Mineral Resources of Xizang Autonomous Region (1993), Lombardo *et al.* (1993) and Carosi *et al.* (1998). Thick barbed lines are the Main Central Thrust I and II, thin barbed line is the South Tibetan Detachment System, and solid lines are faults. Grey dashed line is the approximate political boundary between Nepal (to the south) and China (to the north). (c) Schematic north-south cross-sections of the region west of the Ama Drime Range, summarizing tectonic relationships between the different units (modified from Bordet, 1961; fig. 6). Traces of the cross-sections are indicated in (b).

by a Lu–Hf isochron on garnet, omphacite and whole rock in mafic eclogite and by a U–Pb SHRIMP dating of zircon from a quartzofeldspathic gneiss (De Sigoyer *et al.*, 2000; Leech *et al.*, 2005).

Similarly, coesite relics were discovered as inclusions in omphacite of a few Kaghan eclogites (O'Brien *et al.*, 2001) and as inclusions in zircon in felsic and pelitic gneisses (Kaneko *et al.*, 2003). For the coesite-bearing eclogite, peak metamorphic conditions of 725 ± 25 °C and 2.8–3.0 GPa have been derived from the garnet–pyroxene–phengite assemblage (O'Brien *et al.*, 2001). Metamorphic conditions of 610 ± 30 °C at 2.4 ± 0.2 GPa, just outside the coesite field, have been derived for coesite-free, barroisite-bearing eclogites from the same lithotectonic unit (Lombardo *et al.*, 2000). The Kaghan eclogites show a decompressional re-equilibration which occurred at decreasing temperatures, in contrast with the exhumation path at constant or increasing temperatures of the Greater Himalayan Sequence in India and Nepal (Lombardo & Rolfo, 2000; Treloar *et al.*, 2003). The peak metamorphic stage has been dated at 49 ± 6 Ma using the Sm–Nd method in garnet–clinopyroxene (Tonarini *et al.*, 1993) and at 46.2 ± 0.7 Ma using the SHRIMP U–Pb method on zircon (Kaneko *et al.*, 2003).

In contrast to the NW Himalaya, the eclogites discovered in the Ama Drime Range of the Eastern Himalaya (Lombardo *et al.*, 1998) have a strong granulite-facies overprint at temperatures of ~ 750 °C and pressures of 0.7–1.0 GPa, and followed a clockwise decompression path, convex towards high metamorphic temperatures (Lombardo & Rolfo, 2000).

Such discoveries have important implications for models of India–Eurasia collision and Himalayan tectonics. However, whereas the *P–T* path followed by the NW Himalaya eclogites is now well constrained by petrological and geochronological studies, that of the Eastern Himalaya eclogites has so far been the object of a preliminary study only (Lombardo & Rolfo, 2000). To mitigate this deficiency, in this paper the granulite-facies overprint of the Eastern Himalaya eclogites is described in detail and the *P–T* path is constructed by means of *P–T* pseudosections and conventional geothermobarometry. *P–T* data on the last portion of the *P–T* path are also obtained from the biotite + garnet + plagioclase + sillimanite host gneiss. Such evolution is compared with the *P–T* paths followed by the adjacent non-eclogitic units and with the decompressional *P–T* path recorded in the eclogites from the NW Himalaya.

GEOLOGICAL SETTING

Tumlingtar-Kharta transect

The Nepal Himalaya and adjoining southern Tibet consist of roughly parallel, east–west-trending, laterally continuous lithotectonic units, separated by large-scale thrust systems dipping to the north (Fig. 1a).

From south to north, these units are the molasse sediments of the Sub-Himalaya, the Lesser Himalayan Zone, the Greater Himalayan Sequence (GHS) and the Tethyan Sedimentary Sequence (Upreti, 1999). The GHS is the composite unit of medium- to high-grade metamorphic rocks tectonically interposed between the non-metamorphic to amphibolite facies Lesser Himalaya (below and to the south) and the anchi-metamorphic sedimentary rocks of the Tethyan Himalaya (above and to the north). The GHS is separated from the Lesser Himalayan Zone by the south-verging Main Central Thrust (MCT) and from the Tethyan Sedimentary Sequence by the South Tibetan Detachment System (STDS).

In the eastern Nepal Himalaya, arch-like structures of regional extent deflect to the north the regional east–west trend of lithotectonic contacts. The Ama Drime Range lies in the core of one of such structure, the Arun trans-anticline (Bordet, 1961), a broad north–south arch tapering to the north, that dominates the regional tectonic structure from the lower Arun Valley to the southern Tibetan plateau north-east of Mt Everest (Fig. 1b). Erosion has exposed the Arun Window, which offers a complete section of the north-dipping Himalayan nappe pile from the Lesser Himalayan Tumlingtar Unit (a thick sequence of Precambrian phyllites and quartzites) at the bottom, to the granulite-facies GHS of the upper Arun (Phung Chu) Valley and the Tethyan Sedimentary Sequence at the top (Fig. 1c).

North of the Tumlingtar airstrip along the well-known Makalu trek, a large body of granitic orthogneiss (the 'Migmatites du Bas Himalaya' of Bordet, 1961; the Num Orthogneiss of Brunel, 1983 and Lombardo *et al.*, 1993) is crossed up to Seduwa and was mapped by Bordet & Latreille (1958) on both sides of the Arun Gorge up to the Popti La and Kang La on the Tibetan border.

Thrust sheets and a ductile shear zone (Bordet, 1961; Meier & Hiltner, 1993) separate the Tumlingtar Unit from the overlying Num Orthogneiss. This is the Main Central Thrust I (MCT I; *sensu* Arita, 1983) (Fig. 1c). Because of their distinctly higher metamorphic grade relative to the lower-grade, Lesser Himalayan metasediments, the Num Orthogneiss and the associated metasediments will be called here Lesser Himalayan Crystalline Sequence (LHCS), as in western-central Nepal (Upreti, 1999) and further west in the Sutlej Valley of Himachal Pradesh, India (Vannay *et al.*, 2004 and references therein). The Num Orthogneiss is metamorphosed at amphibolite facies (Brunel & Kienast, 1986; Pognante & Benna, 1993; Goscombe & Hand, 2000). Metamorphic equilibration temperatures increase towards structurally higher levels (inverted metamorphism), from 400 to 500 °C at the top of the Tumlingtar Unit to higher than 600 °C in the LHCS (Brunel & Kienast, 1986; Pognante & Benna, 1993; Goscombe & Hand, 2000). Strongly overprinted eclogites were found by Parkinson & Kohn (2002) as

rare relics in discontinuous amphibolitized layers and boudins within quartzofeldspathic gneisses between Hatiya and Chepuwa villages, north of Num.

Metasedimentary and metagranitic thrust sheets with amphibolites separate the Num Orthogneiss of the LHCS from the overlying Barun Gneiss, the basal unit of the GHS (Bordet, 1961; Brunel, 1983; Lombardo *et al.*, 1993). This is the Main Central Thrust II (MCT II; *sensu* Arita, 1983) (Fig. 1c). Along the Makalu trek, the Barun Gneiss is best exposed north of Seduwa and in the Barun Valley, where it was studied by Bordet (1961), Pognante & Benna (1993) and Goscombe & Hand (2000).

A gap in geological information exists between the Barun-Makalu section and the southern side of the lower Kama Chu Valley, but on the northern side of the Kama Chu Valley, lithologies very similar to the Barun Gneiss are well exposed and can be traced continuously through the Shao La to the Kharta (Karda) region of the Phung Chu (upper Arun) Valley, east of the Mt Everest–Makalu massif. In this area, the GHS is a 6–7 km thick metamorphic sequence dipping gently to the west (Hagen, 1969), in which the lower section (Kharta Gneiss Complex) consists of garnet-bearing metapelite, with minor metabasite and calc-silicate rock, equilibrated in the upper amphibolite to granulite facies (Borghi *et al.*, 2003). The Kharta Gneiss hosts bodies of migmatitic, sillimanite- and cordierite-bearing orthogneiss possibly correlative with the Lower Palaeozoic Namche Migmatite Orthogneiss exposed westwards in the Dudh Kosi Valley (Tonarini *et al.*, 1994; Viskupic & Hodges, 2001; Catlos *et al.*, 2002). Migmatized Kharta gneiss is especially well developed in the lower Kharta Chu Valley and along the western side of the Phung Chu Valley, where several generations of leucosomes are conspicuous and range in morphology from concordant leucogranitic orthogneiss containing garnet and prismatic sillimanite after kyanite, to discordant cordierite-bearing leucogranite veins and pods. Both the concordant leucogranitic orthogneiss and the discordant leucogranite veins are crosscut by Miocene leucogranite dykes (Visonà & Lombardo, 2002).

The GHS is bounded at the top by extensional ductile to brittle shear zones (Burg *et al.*, 1984; Burchfiel *et al.*, 1992; Carosi *et al.*, 1998; Searle, 1999), the STDS of Burchfiel *et al.* (1992) well displayed in the Dzakar Chu gorge (Burg *et al.*, 1984; Cottle *et al.*, 2006). Further to the south-west, in the Everest massif, the STDS separates the greenschist-facies North Col Formation of Late Proterozoic–Early Cambrian age (and the overlying Cambrian to Eocene Tethyan Sedimentary Series) in its hangingwall, from footwall biotite-sillimanite gneiss and biotite-muscovite gneiss (Burchfiel *et al.*, 1992; Pognante & Benna, 1993). Phase compatibilities and geothermobarometric data point to temperatures of metamorphic equilibration over 700 °C in the upper GHS. Temperatures decrease down to ~600 °C in the ductile portion of the STDS,

where muscovite, staurolite and cordierite are stable and metamorphic isograds are strongly telescoped (Colombo *et al.*, 1995; Jessup *et al.*, 2004).

Networks of dykes, sheet-like bodies and large laccolithic plutons of leucogranite occur in the GHS of the Phung Chu, upper Kama and Kharta Valleys, in the North Col Formation, and very rarely also in the Ordovician limestones of the Tethyan Sedimentary Series (Visonà & Lombardo, 2002). The granite plutons may attain a thickness of 1–2 km (Makalu) and evolve into cylindrical bodies with gentle N-plunging longest axes, as may be seen in the south face of the Nuptse–Lhotse ridge. The Makalu and Nuptse plutons are composed of two-mica granite intruded by tourmaline granite, while the dykes in the upper GHS are mainly two-mica granite, with a few tourmaline granites (e.g. Rongbuk Gompa). The middle and lower GHS (Phung Chu, Kharta and Kama Valleys) host discordant two-mica (biotite-rich with andalusite-sillimanite-cordierite) leucogranite dykes. The generation and cooling of leucogranites in the Everest–Makalu region fall in the Early–Middle Miocene, between 24 and 16 Ma (Ferrara *et al.*, 1983; Schärer, 1984; Schärer *et al.*, 1986; Hodges *et al.*, 1998; Murphy & Harrison, 1999; Simpson *et al.*, 2000).

Ama Drime Range

Ama Drime Range, from its most prominent peak (6669 m), is the name used here for the north–south-trending range lying to the east of the Phung Chu (upper Arun Valley) and to the west of the Yaru Chu, the eastern tributary of the Phung Chu. This range, also known as the Gyankar Range in the reports of British expeditions to Mt Everest (e.g. Howard Bury, 1922), has an antiformal structure, with metamorphic foliation dipping to the west in the Phung Chu Valley (Kharta) and to the east of Sangkar Ri in the Yaru Chu Valley. The geology of the west side was investigated by Lombardo *et al.* (1998), Lombardo & Rolfo (2000) and Visonà & Lombardo (2002); the geology of the east side by Burchfiel *et al.* (1992); while the sedimentary region west, north and east of the Range is shown in the maps of Wager (1934), Burg (1983) and Bureau of Geology and Mineral Resources of Xizang Autonomous Region (1993).

The western side of the Ama Drime Range is mostly comprised of granitic orthogneisses, in places migmatitic, with intercalations and rafts of metapelite and transposed dykes of garnet amphibolite with eclogite relics. Both two-mica and tourmaline leucogranite dykes are present in the granitic orthogneisses, but the leucogranites involved in the MCT II Zone near Kharta (see below) are exclusively composed of tourmaline leucogranite (Visonà & Lombardo, 2002).

Along the Phung Chu Valley north of Kharta, the high-grade rocks of the Kharta Gneiss Complex are separated from the underlying granitic orthogneisses of the Ama Drime Range by a north-trending belt of

thrust sheets of granitic orthogneiss with garnet-amphibolite, quartzite and mylonitic marble (Lombardo *et al.*, 1998; Lombardo & Rolfo, 2000). This geological setting is strikingly similar to the tectonic sequence observed north of Seduwa in the core of the Arun window (Bordet, 1961; Lombardo *et al.*, 1993), where metasedimentary and metagranitic thrust sheets with amphibolites separate the granitic Num Orthogneiss belonging to the LHCS from the overlying Barun Gneiss, the basal unit of the GHS that is lithologically identical with the Kharta Gneiss Complex. This suggests that the Ama Drime orthogneiss may be analogous to the Num Orthogneiss and as such belongs to the LHCS. The thrust surface bounding the Ama Drime orthogneiss to the west is a major lithotectonic break, as indicated by the difference in Sm/Nd model ages of Tertiary leucogranites. These average 2.0 Ga in the GHS leucogranites and 2.9 Ga in the leucogranites hosted in the thrust sheets and further downsection in the granitic orthogneiss of the Ama Drime Range (Visonà *et al.*, 2000). Such model ages are consistent with those determined by Robinson *et al.* (2001) on paragneisses from the base of the GHS and from granitic orthogneisses of the Lesser Himalayan Zone in eastern Nepal, which average 2.0 and 2.5 Ga, respectively.

The granulitized eclogites studied here occur as boudinaged dykes and small bodies within the granitic orthogneisses of the Ama Drime Range. They were found during the 1997 field season in outcrops south-east of Kharta, along the eastern side of the Phung Chu Valley (Lombardo *et al.*, 1998). In the 1999 and 2002 field seasons, eclogites were found also in the east-west-trending valleys leading from the Phung Chu towards the interior of the Ama Drime range, in particular, in the Belung and Tanghyu Valleys (Fig. 2). In all of this region, the granulitized eclogites are hosted within granitic orthogneisses mainly consisting of K-feldspar, plagioclase, quartz and biotite, with layers and intercalations of garnet-sillimanite-biotite gneisses and restitic garnet-biotite-sillimanite-gedrite-cordierite schists.

PETROGRAPHY

The studied sample EV02-42, from Tanghyu Valley, is very similar to the granulitized eclogites described by Lombardo & Rolfo (2000) from the region south-east of Kharta, although it better preserves evidence of the eclogitic and granulitic stages. It is an undeformed, fine-grained rock, mainly consisting of garnet, clinopyroxene, plagioclase, brown amphibole, quartz, and minor orthopyroxene, biotite and ilmenite.

On the basis of microstructural observations and mineral relationships, four mineral assemblages have been recognized: (i) eclogite-facies assemblage M1; (ii) peak-*T* granulite-facies assemblage M2; (iii) plagioclase + orthopyroxene corona around garnet M3, also developed under granulitic facies conditions, and

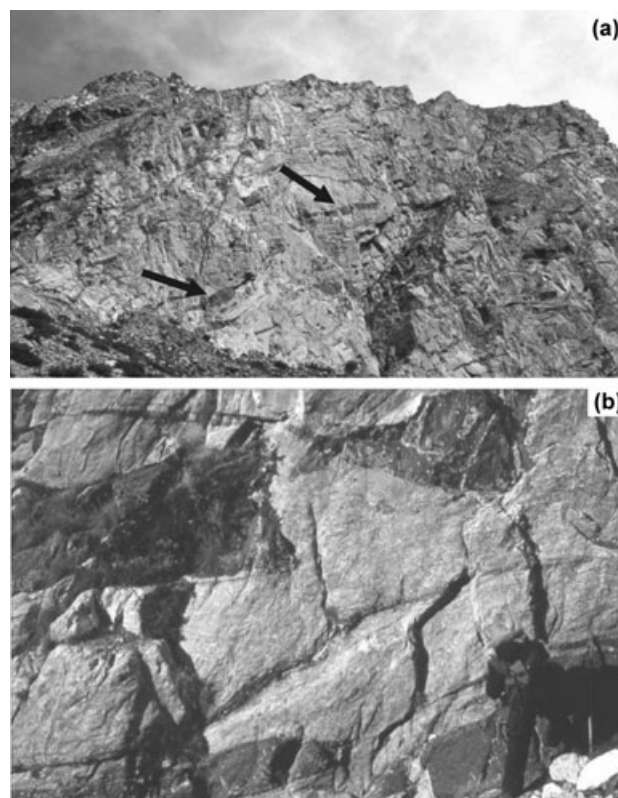


Fig. 2. (a) Arrows point to boudinaged dykes of granulitized eclogite in the granitic orthogneiss, Tanghyu Valley, western side of the Ama Drime Range, north of Kharta. View looking north. (b) A detail of the boudinaged dykes, Tanghyu Valley. View looking north.

(iv) brown amphibole + plagioclase assemblage M4, resulting from an amphibolite-facies overprint. The same petrological observations may be extended to the other eclogite samples collected by the present authors in the Ama Drime Range (24 in all). Other descriptions of representative eclogite samples are given by Lombardo & Rolfo (2000), Liu *et al.* (2005) and Ferrando *et al.* (2006).

Eclogite assemblage (M1)

The eclogite-facies paragenesis, consisting of garnet, omphacite and minor phengite, was mainly lost during the granulite-facies overprinting at the metamorphic thermal peak. Ca-rich cores of the large garnet crystals, crowded with small quartz and rutile inclusions, probably represent relics of the eclogitic assemblage, only partially re-equilibrated during the metamorphic thermal peak. Eclogitic omphacite is not preserved, being replaced by a fine-grained symplectite of clinopyroxene + plagioclase, locally transformed into fine-grained orthopyroxene (Figs 3a,b & 4b,c) (Zhao *et al.*, 2001). Inclusions of relatively Na-rich clinopyroxene (Jd₁₆), plotting in the diopside field of the Morimoto (1988) diagram close to the omphacite field (Fig. 6),

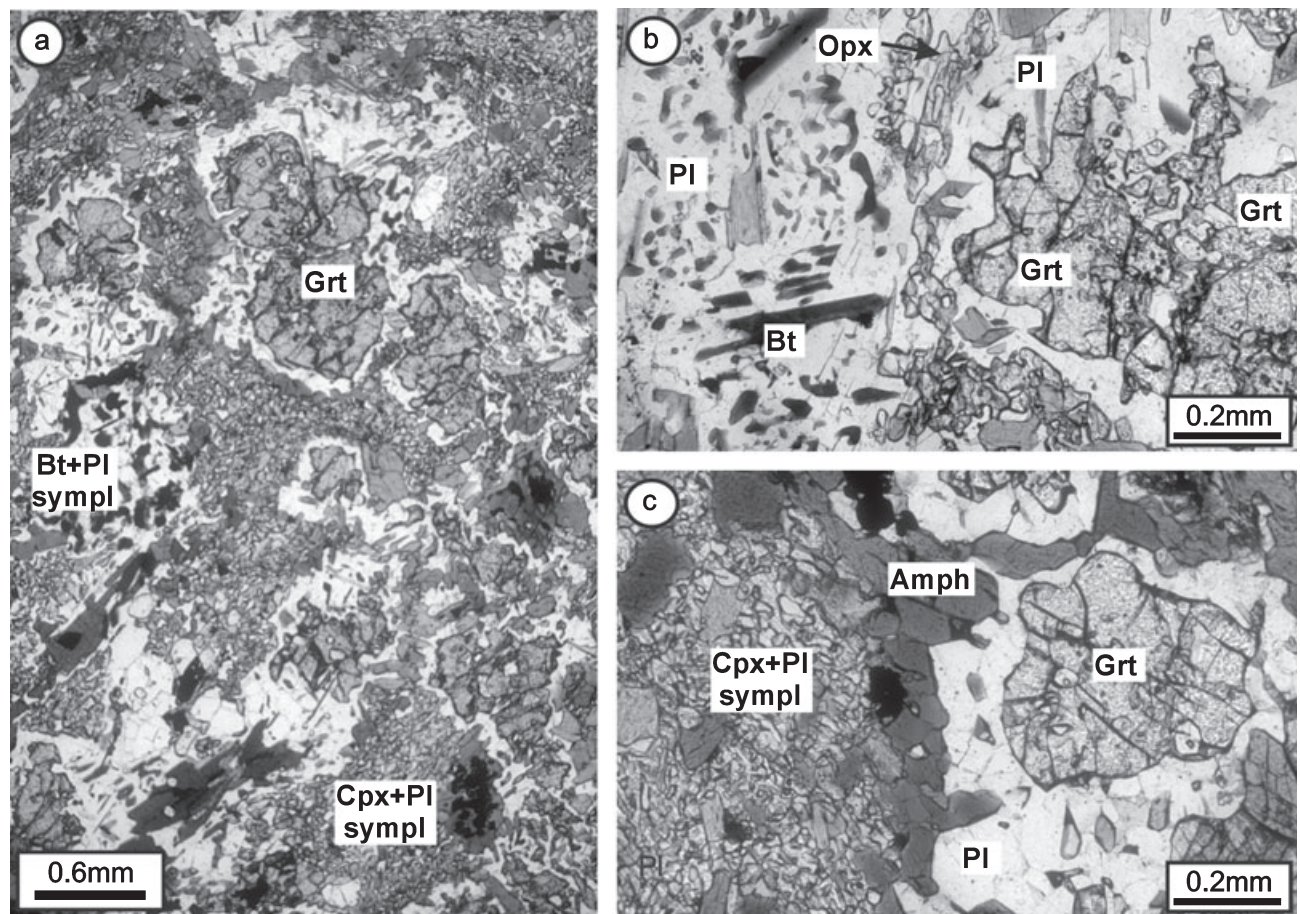


Fig. 3. Representative microstructure of the granulitized eclogite EV02-42. (a) Large garnet (Grt) surrounded by a plagioclase + orthopyroxene corona, set in a symplectite of clinopyroxene + plagioclase after omphacite (Cpx + Pl sympl). Biotite + plagioclase symplectite after phengite is also evident. (b) Detail of the plagioclase (Pl) + orthopyroxene (Opx) corona around garnet and of the plagioclase + biotite symplectite after phengite. Note that the garnet core is crowded with small quartz inclusions, whereas the mantle is free of inclusions. (c) Detail of the plagioclase (Pl) corona around garnet (Grt) and of the clinopyroxene + plagioclase symplectite after omphacite (Cpx + Pl sympl). Small crystals of brown amphibole grow in the clinopyroxene + plagioclase symplectite, while larger amphibole crystals (Amph) grow at the interface between the symplectite and the corona around garnet.

are locally preserved in garnet cores (see also EV97-45; Fig. 6). These Na-rich pyroxene may represent a prograde inclusion rather than an eclogitic pyroxene. Although omphacite is not preserved either in the matrix or in the garnet core, the clinopyroxene + plagioclase symplectitic texture has been reported from many retrogressed eclogites and high-pressure granulites, and is thought to indicate the replacement of omphacite by plagioclase and clinopyroxene formed during the transition from eclogite to high-pressure granulite facies (Heinrich, 1982; O'Brien, 1990; Rubie, 1990; Joanny *et al.*, 1991; Smelov & Beryozkin, 1993; Möller, 1998; Lombardo & Rolfo, 2000; Zhao *et al.*, 2001).

Phengite is completely replaced by a symplectite consisting of red biotite and plagioclase (Figs 3a,b & 4d). Phengite was not observed as an inclusion in garnet core regions, nor in the EV02-42 sample or in the other samples from the same locality.

Thermal peak assemblage (M2)

The metamorphic peak-*T* assemblage is represented by relatively coarse-grained clinopyroxene, orthopyroxene, garnet, plagioclase and accessory ilmenite. The garnet mantle grown during this stage is characterized by the absence of quartz inclusions, that are instead present in the poikiloblastic core (Fig. 3b). This suggests that quartz was involved in some quartz-consuming reactions during the metamorphic evolution from the eclogitic to the granulitic peak stage (e.g. the Cpx + Pl symplectite formation reaction). Orthopyroxene is rarely preserved in the rock matrix, being partially replaced by amphibole.

Plagioclase + orthopyroxene corona (M3)

A second, lower-pressure, granulitic stage is represented by the development of a plagioclase + orthopy-

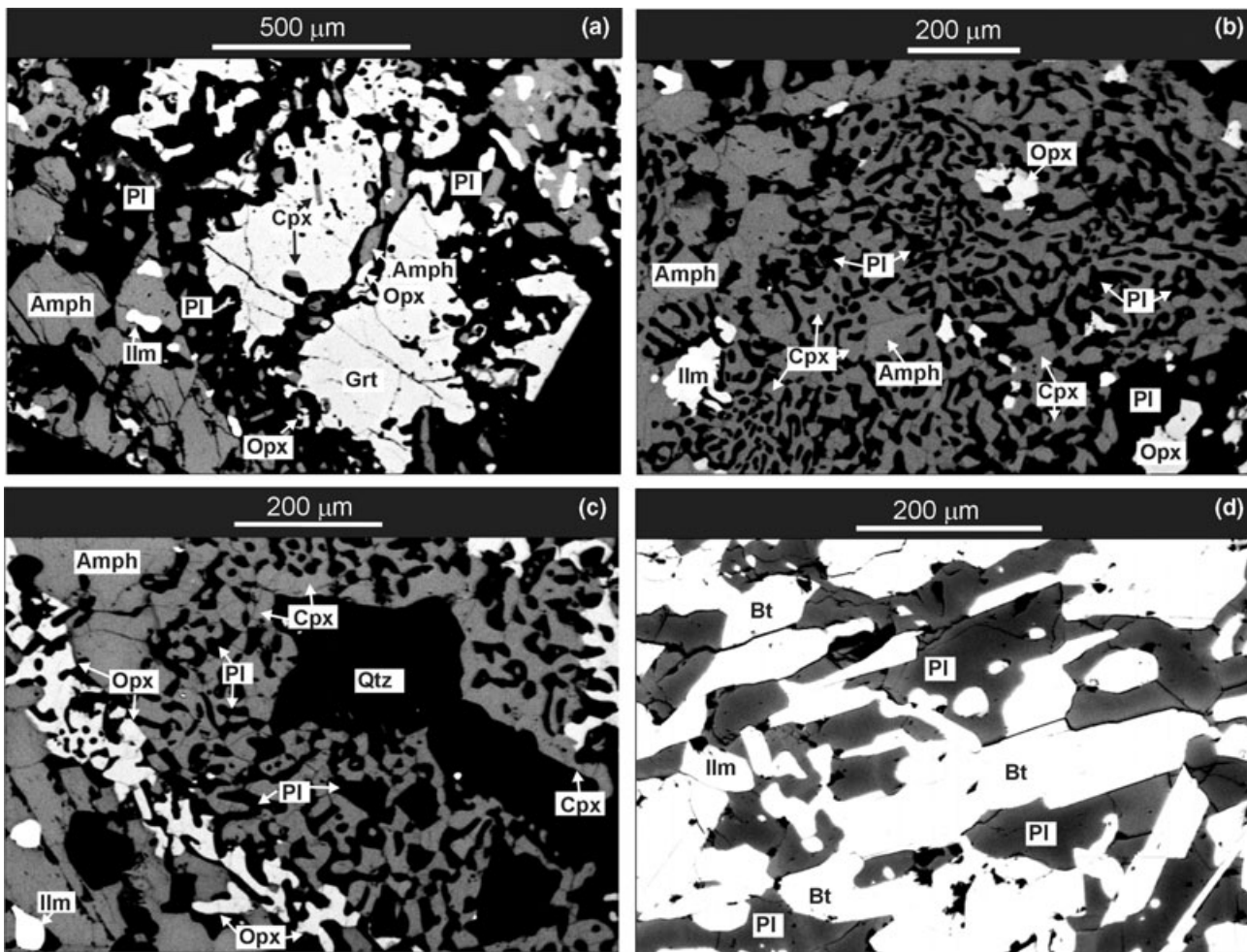


Fig. 4. Back-scattered electron images of the granulitized eclogite EV02-42. (a) Large garnet (Grt) crystal surrounded by a corona of plagioclase (Pl) + orthopyroxene (Opx). (b) Fine-grained symplectite of clinopyroxene (Cpx) + plagioclase (Pl) ± amphibole (Amph) ± orthopyroxene (Opx) replacing earlier omphacite. (c) Clinopyroxene (Cpx) + plagioclase (Pl) symplectite after omphacite rimmed by fine-grained orthopyroxene (Opx). (d) Biotite (Bt) + plagioclase (Pl) symplectite after phengite. Plagioclase is zoned, showing a Na-rich core.

roxene ± amphibole corona around garnet. Elongated plagioclase crystals occur in the inner part of the corona, adjacent to garnet, whereas orthopyroxene is found in the outer corona, together with accessory ilmenite and local amphibole (Figs 3b,c & 4a). Coronitic textures like these have been observed in many other granulitic terranes and are considered to indicate decompression following peak granulite-facies metamorphism (e.g. Harley, 1989, 1992; Kumar & Chacko, 1991; Thost *et al.*, 1991; Zhao *et al.*, 2001).

Brown amphibole + plagioclase assemblage (M4)

The last metamorphic stage recorded by the granulitized eclogite EV02-42 is represented by the widespread growth of brown amphibole in the rock matrix. Brown amphibole, in equilibrium with a Na-rich plagioclase, also grows in the clinopyroxene + plagioclase symplectite after omphacite (Fig. 4b,c) and in

the plagioclase + orthopyroxene corona around garnet (Fig. 3c).

MINERAL CHEMISTRY

Garnet, plagioclase, clinopyroxene, orthopyroxene, amphibole and biotite were analysed with a Cambridge Stereoscan 360 SEM equipped with an EDS Energy 200 and a Pentafet detector (Oxford Instruments) at the Department of Mineralogical and Petrological Sciences, University of Torino, Italy. The operating conditions were: 50 s counting time, 15 kV accelerating voltage and 2.70–2.80 A beam current. SEM-EDS quantitative data (spot size = 2 μm) were acquired and processed using the Microanalysis Suite Issue 12, INCA Suite version 4.01; the raw data were calibrated on natural mineral standards and the $\Phi\rho Z$ correction (Pouchou & Pichoir, 1988) was applied. Representative SEM-EDS analyses of selected miner-

Table 1. Representative SEM-EDS analyses of garnet (EV02-42).

Point analysis	Crystal A					Crystal B						Crystal C						
	7.8 Mantle	7.9 Mantle	7.10 Core	7.11 Mantle	7.12 Rim	14.1 Rim	14.2 Mantle	14.3 Core	14.4 Mantle	14.5 Mantle	14.6 Rim	14.7 Rim	14.8 Mantle	14.9 Core	14.10 Mantle	14.11 Mantle	14.12 Mantle	14.13 Mantle
SiO ₂	37.88	37.34	37.68	37.58	37.25	36.83	37.20	37.55	37.61	37.30	36.92	37.19	37.75	37.77	37.15	37.54	37.41	37.41
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35
Al ₂ O ₃	20.61	20.79	21.00	20.93	20.96	20.50	20.86	20.69	20.93	20.70	20.64	20.67	21.03	20.88	20.68	20.87	20.43	20.64
Fe ₂ O ₃	2.11	3.00	2.81	3.40	2.62	3.35	3.63	3.09	3.48	4.21	3.89	2.96	2.99	2.37	3.71	3.54	3.75	2.69
FeO	25.07	24.60	23.15	22.77	26.44	26.41	23.75	23.82	23.60	23.41	24.87	26.67	24.26	24.41	22.84	23.65	23.14	23.75
MnO	1.30	0.82	0.00	0.75	1.29	1.35	0.76	0.59	0.64	0.57	1.42	1.45	0.00	0.00	0.61	0.57	0.47	0.98
MgO	2.75	2.97	3.44	3.42	3.40	3.04	3.18	3.23	3.31	3.25	2.90	3.38	3.39	3.45	3.35	3.32	3.32	3.34
CaO	10.93	10.86	12.31	11.95	8.39	8.48	11.16	11.49	11.57	11.57	9.89	8.05	11.58	11.40	11.70	11.51	11.87	11.20
Total	100.65	100.39	100.39	100.80	100.35	99.96	100.55	100.46	101.14	101.01	100.54	100.37	101.00	100.28	100.04	100.99	100.38	100.36
Si	2.98	2.94	2.95	2.94	2.95	2.94	2.93	2.95	2.94	2.92	2.92	2.95	2.95	2.96	2.93	2.93	2.94	2.94
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Al	1.91	1.93	1.94	1.93	1.95	1.93	1.93	1.92	1.93	1.91	1.93	1.93	1.93	1.93	1.92	1.92	1.89	1.91
Fe ³⁺	0.12	0.18	0.17	0.20	0.16	0.20	0.22	0.18	0.20	0.25	0.23	0.18	0.18	0.14	0.22	0.21	0.22	0.16
Fe ²⁺	1.65	1.62	1.52	1.49	1.75	1.76	1.56	1.57	1.54	1.53	1.65	1.77	1.58	1.60	1.51	1.55	1.52	1.56
Mn	0.09	0.05	0.00	0.05	0.09	0.09	0.05	0.04	0.04	0.04	0.09	0.10	0.00	0.00	0.04	0.04	0.03	0.07
Mg	0.32	0.35	0.40	0.40	0.40	0.36	0.37	0.38	0.39	0.38	0.34	0.40	0.39	0.40	0.39	0.39	0.39	0.39
Ca	0.92	0.92	1.03	1.00	0.71	0.72	0.94	0.97	0.97	0.97	0.84	0.68	0.97	0.96	0.99	0.96	1.00	0.94
Grs	0.25	0.22	0.27	0.24	0.16	0.14	0.21	0.24	0.23	0.21	0.17	0.14	0.24	0.25	0.23	0.22	0.23	0.23
Alm	0.55	0.55	0.51	0.51	0.59	0.60	0.53	0.53	0.53	0.53	0.56	0.60	0.54	0.54	0.51	0.53	0.52	0.53
Prp	0.11	0.12	0.14	0.14	0.14	0.12	0.13	0.13	0.13	0.13	0.12	0.14	0.13	0.14	0.13	0.13	0.13	0.13
Sps	0.03	0.02	0.00	0.02	0.03	0.03	0.02	0.01	0.01	0.01	0.03	0.03	0.00	0.00	0.01	0.01	0.01	0.02
Andr	0.06	0.09	0.08	0.10	0.08	0.10	0.11	0.09	0.10	0.13	0.12	0.09	0.09	0.07	0.11	0.11	0.11	0.08

Fe³⁺ was recalculated according to stoichiometry.

als are reported in Tables 1–4. In Figs 5 and 6, the compositional fields of garnet and clinopyroxene from additional representative eclogite samples (EV97-44, EV97-45 and EV02-45) have been reported.

Garnet

Garnet is an Alm-Grs-Prp solid solution with the almandine component ranging between 49 and 60 mol.% and the spessartine component < 5 mol.% (Fig. 5 & Table 1). Ca and Fe show a coupled zoning, with grossular decreasing from 27–28 mol.% in the poikiloblastic core to 20–25 mol.% in the inclusion-free mantle, balanced by almandine increasing from 49 to 55 mol.%. Pyrope and spessartine components are quite constant across the garnet (Prp_{11–14} and Sps_{0–3}). Garnet from the other analysed samples (EV97-44, EV97-45 and EV02-45) shows the same zonation trend (Fig. 5). As already reported by Zhao *et al.* (2001) for garnet occurring in granulitized eclogites, the outermost rim, ~0.5 mm wide, has a low grossular content (Grs_{13–15}) and a high almandine (Alm_{58–60}) and spessartine content (Sps₄), which reflects resetting by diffusion and/or net-transfer reactions during the post-thermal peak cooling.

Clinopyroxene

Clinopyroxene occurs both in the symplectite after omphacite and in the rock matrix. Both the matrix-type and symplectitic clinopyroxene are diopside, with the aegirine component < 5 mol.% and the jadeite component equal to zero (Fig. 6 & Table 2). X_{Mg} [$X_{Mg} = Mg/(Mg + Fe)$] varies from 0.60 to 0.70.

Clinopyroxene included in garnet rims shows the same composition as in the rock matrix. Rare clinopyroxene inclusions in garnet cores are characterized by jadeite content up to 16 mol.% (Fig. 6) and are plotted in the diopside compositional field (Morimoto, 1988), close to the omphacite field. These Na-clinopyroxene may be interpreted as prograde inclusions rather than eclogitic pyroxene. A similar Na-rich clinopyroxene was also observed in EV97-45 (Fig. 6).

Plagioclase

Plagioclase occurring in different microstructural sites has widely different chemical compositions (Fig. 7 & Table 3). Compositional features of the different plagioclase domains include the following:

- 1 Plagioclase hosted in garnet mantle is a labradorite and shows the highest anorthite content, up to An₆₅.
- 2 Elongated plagioclase crystals occurring in the plagioclase + orthopyroxene ± amphibole corona around garnet are labradorite, but less calcic than plagioclase inclusions in garnet. Corona plagioclase composition ranges between An₅₀ and An₅₇, with the more Ca-rich compositions adjacent to garnet.
- 3 Plagioclase in the symplectite after omphacite is an andesine and shows irregular zoning from An₄₀ to An₄₈, the Na-rich compositions being generally adjacent to quartz.
- 4 Plagioclase in the symplectite after phengite is strongly zoned with an oligoclase core (An_{21–25}) and a labradorite rim (An_{55–57}) adjacent to biotite flakes (Fig. 4d).
- 5 Plagioclase in equilibrium with brown amphibole in the rock matrix varies in composition from oligoclase to andesine (An_{29–35}).

Table 2. Representative SEM-EDS analyses of clino- and orthopyroxene (EV02-42).

Point analyses	6.1	6.3 ^a	9.6	10.7	14.18
				In Grt core	In Grt rim
Clinopyroxene					
SiO ₂	51.96	50.27	49.92	51.30	48.85
Al ₂ O ₃	0.81	2.09	0.92	7.70	3.12
Fe ₂ O ₃	2.24	4.83	5.39	1.98	4.61
FeO	9.61	6.99	10.63	7.19	8.13
MnO	0.00	0.00	0.50	0.00	0.00
MgO	12.42	11.88	10.25	9.47	10.79
CaO	23.72	23.48	22.51	19.57	23.63
Na ₂ O	0.00	0.40	0.31	2.63	0.35
Total	100.77	99.95	100.44	99.84	100.42
Si	1.95	1.90	1.91	1.90	1.86
Al ^{IV}	0.04	0.09	0.04	0.10	0.14
Fe ³⁺	0.01	0.01	0.05	0.00	0.00
Sum T	2.00	2.00	2.00	2.00	2.00
Al ^{VI}	0.00	0.00	0.00	0.23	0.00
Fe ³⁺	0.05	0.13	0.11	0.06	0.16
Fe ²⁺	0.30	0.22	0.34	0.22	0.23
Mn	0.00	0.00	0.02	0.00	0.00
Mg	0.69	0.67	0.59	0.52	0.61
Ca	0.95	0.95	0.92	0.78	0.97
Na	0.00	0.03	0.02	0.19	0.03
Point analyses	6.8 ^a	9.7	9.12	14.22	14.24
	Syml Omph	Syml Omph	Syml Omph	Grt corona	Grt corona
Orthopyroxene					
SiO ₂	50.62	48.77	49.42	50.12	50.17
Al ₂ O ₃	0.77	0.56	0.88	0.85	0.81
Fe ₂ O ₃	1.73	2.19	1.33	2.19	2.15
FeO	29.97	33.31	33.95	32.06	31.01
MnO	0.57	0.82	0.50	0.42	0.61
MgO	16.41	13.10	13.22	14.87	15.37
CaO	0.57	0.65	0.84	0.74	0.76
Total	100.64	99.40	100.14	101.25	100.88
Si	1.96	1.95	1.96	1.95	1.95
Al ^{IV}	0.04	0.03	0.04	0.04	0.04
Sum T	1.99	1.98	2.00	1.99	1.99
Al ^{VI}	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	0.05	0.07	0.04	0.06	0.06
Fe ²⁺	0.97	1.12	1.13	1.04	1.01
Mn	0.02	0.03	0.02	0.01	0.02
Mg	0.95	0.78	0.78	0.86	0.89
Ca	0.02	0.03	0.04	0.03	0.03

Fe³⁺ was recalculated according to stoichiometry.^aCompositions of clinopyroxene and orthopyroxene used for the thermobarometric estimates.

Orthopyroxene

No significant differences in chemical composition have been observed for the matrix-type and symplectitic or coronitic orthopyroxene. X_{Fe} [$X_{\text{Fe}} = \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$] ranges from 0.51 to 0.59 and the Ca content is < 5 mol.% (Table 2).

Amphibole

Brown amphibole occurring in the rock matrix, in the symplectite after omphacite and in garnet coronas shows a rather constant chemical composition. Amphibole is slightly zoned, with Na and Al^{VI} contents decreasing from core to rim (Table 4). According to the classification of Leake *et al.* (1997), its compo-

sition ranges from pargasite to ferropargasite (Fig. 8a) and is plotted at the granulite-amphibolite facies transition in the Zakrutkin (1968) amphibole diagram (Fig. 8b).

P–T EVOLUTION OF THE GRANULITIZED ECLOGITE

The metamorphic evolution of granulitized eclogite EV02-42 was mainly reconstructed by combining microstructural observations and *P–T* pseudosection analysis. As a result of the lack of eclogitic relics, *P–T* conditions during this stage have been estimated only roughly. In contrast, the peak granulitic assemblages (M2) and the plagioclase + orthopyroxene corona around garnet (M3) give useful constraints for the post-eclogitic *P–T* trajectory. The results obtained using the *P–T* pseudosection approach are consistent with the *P–T* estimates given by conventional thermobarometry applied to the M3 and M4 assemblages.

P–T pseudosection calculation

To model eclogitic M1, thermal-peak M2, and retrograde M3 and M4 metamorphic conditions, a first *P–T* pseudosection (pseudosection 1, Fig. 9) was calculated at fixed bulk-rock composition (e.g. Hensen, 1971; Zeh, 2001) in the model NCKFMASH + Ti system. The bulk-rock composition measured with ICP-MS by ALS Chemex, Vancouver, Canada, is: Na₂O = 2.61%, MgO = 6.79%, Al₂O₃ = 13.50%, SiO₂ = 48.00%, K₂O = 0.25%, CaO = 11.00%, FeO = 15.30%, TiO₂ = 1.80% (wt%). Although garnet crystals are zoned with a Ca-rich eclogitic core and a Ca-poorer granulitic mantle, this bulk-rock composition is probably not significantly affected by the garnet fractionation process (Vance & Mahar, 1998), because garnet cores are small compared with the size of garnet crystals, and the difference in Ca-content between eclogitic cores and granulitic mantles is low. For this reason, the measured bulk-rock composition has been considered as the effective composition (Stüwe, 1997), without subtracting from the model system the amount of Ca corresponding to the relict eclogitic core (Marmo *et al.*, 2002; Evans, 2004). The use of a constant bulk-rock composition is also justified by the lack of evidence of metasomatism occurring during the decompressional evolution of the rock. Garnet, amphibole, clinopyroxene and orthopyroxene all contain small amounts of Fe₂O₃, which is higher than 15% of the FeO_{tot} only in clinopyroxene and amphibole, where $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{FeO}) \times 100$ is equal to 14–38% and 15–25%, respectively. Weighing the modal amount of the Fe³⁺-bearing phases and their Fe³⁺ content, Fe₂O₃ in the bulk-rock composition was estimated as 10% of the total FeO; this value is considered as the upper limit.

A second *P–T* pseudosection (pseudosection 2, Fig. 10) was calculated in the NCFMASH system, to

Table 3. Representative SEM-EDS analyses of plagioclase and biotite (EV02-42).

Point analyses	Plagioclase										Biotite		
	7.23	7.30	14.31	6.9 ^a	2.3	16.14	15.5	15.6	14.29	1.6	15.1	15.2	
	Hosted in Grt	Grt corona	Grt corona	Sympl Omph	Sympl Omph	Sympl Omph	Sympl Phe	Sympl Phe	matrix	matrix			
SiO ₂	51.32	55.45	55.33	56.81	58.17	56.88	54.58	63.07	60.98	60.94	36.45	37.04	
Al ₂ O ₃	29.56	27.22	28.28	27.17	26.07	26.84	28.54	23.01	23.91	23.45	5.09	5.01	
FeO	1.75	0.73	0.00	0.66	0.52	0.24	0.00	0.00	0.00	0.46	14.86	14.70	
CaO	13.59	10.92	11.96	9.92	9.08	10.04	12.04	5.18	6.09	6.04	18.05	18.55	
Na ₂ O	4.14	5.50	5.08	6.18	6.47	6.02	5.03	8.42	7.93	8.00	12.32	12.57	
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.24	0.00	0.00	0.00	0.00	
Total	100.55	99.87	100.65	100.74	100.31	100.50	100.19	99.92	98.91	98.89	9.54	9.86	
											Total	96.30	97.71
Si	2.33	2.51	2.49	2.538	2.61	2.55	2.46	2.81	2.75	2.75			
Al	1.58	1.45	1.50	1.430	1.38	1.42	1.52	1.21	1.27	1.25	Si	2.74	2.75
Fe ²⁺	0.07	0.02	0.00	0.022	0.02	0.02	0.00	0.00	0.00	0.02	Al ^{IV}	1.26	1.25
Ca	0.66	0.53	0.58	0.475	0.44	0.48	0.58	0.25	0.29	0.29	Al ^{VI}	0.06	0.04
Na	0.36	0.48	0.44	0.535	0.56	0.52	0.44	0.73	0.69	0.70	Ti	0.29	0.28
K	0.00	0.00	0.00	0.000	0.00	0.01	0.00	0.01	0.00	0.00	Fe ²⁺	1.13	1.15
											Mg	1.38	1.39
Ab	0.36	0.48	0.44	0.53	0.56	0.51	0.43	0.74	0.70	0.71	Na	0.00	0.00
An	0.65	0.52	0.57	0.47	0.44	0.47	0.57	0.25	0.30	0.29	K	0.91	0.93
Or	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00			

^aComposition of plagioclase used for the thermobarometric estimates.

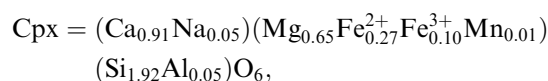
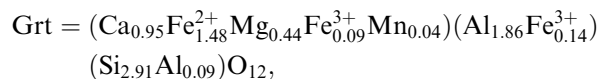
Point analyses	Amph in the matrix					Amph in symplectite after Omph		Amph in the corona around Grt	
	1.1	1.2	1.3	1.4	1.5	9.8	9.11	14.17	14.3
	Rim	Core	Core	Core	Rim				
SiO ₂	42.75	42.43	42.41	42.55	43.81	42.35	42.53	42.00	42.39
TiO ₂	1.40	0.98	1.14	1.28	1.52	1.90	1.91	1.64	1.57
Al ₂ O ₃	11.46	12.16	12.12	11.58	10.92	10.87	11.02	11.18	11.27
Fe ₂ O ₃	4.82	8.04	6.11	4.07	4.59	3.26	4.30	3.84	3.42
FeO	13.12	10.34	11.34	12.82	12.50	17.09	17.05	15.88	15.12
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	10.06	10.74	10.81	10.43	10.98	8.38	8.30	8.80	9.42
CaO	11.73	10.70	11.79	11.97	11.89	11.92	11.99	12.16	12.38
Na ₂ O	1.60	1.54	1.72	1.73	1.54	1.58	1.61	1.51	1.64
K ₂ O	0.52	0.77	0.65	0.59	0.61	0.87	0.78	0.98	0.89
Total	97.46	97.70	98.09	97.02	98.36	98.22	99.49	97.99	98.09
Si	6.40	6.30	6.29	6.39	6.47	6.41	6.36	6.35	6.37
Al ^{IV}	1.60	1.70	1.71	1.61	1.53	1.59	1.64	1.65	1.63
Al ^{VI}	0.42	0.42	0.40	0.44	0.37	0.34	0.30	0.35	0.37
Ti	0.16	0.11	0.13	0.14	0.17	0.22	0.21	0.19	0.18
Fe ³⁺	0.54	0.90	0.68	0.46	0.51	0.37	0.48	0.44	0.39
Fe ²⁺	1.64	1.28	1.41	1.61	1.54	2.16	2.13	2.01	1.90
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	2.24	2.37	2.39	2.33	2.41	1.89	1.85	1.98	2.11
Ca	1.88	1.70	1.87	1.92	1.88	1.93	1.92	1.97	1.99
Na(M4)	0.12	0.30	0.13	0.08	0.12	0.07	0.08	0.03	0.01
Na(A)	0.34	0.14	0.37	0.43	0.32	0.39	0.39	0.41	0.47
K	0.10	0.15	0.12	0.11	0.11	0.17	0.15	0.19	0.17

Fe³⁺ was estimated with the procedure proposed by Holland & Blundy (1994).

model the plagioclase + orthopyroxene corona around garnet (M3). Coronitic textures reflect extremely localized equilibrium conditions and cannot be modelled using the total bulk-rock composition. The composition of the effective reactive micro-domain (Evans, 2004; Groppo *et al.*, 2006) was calculated balancing the reaction $\text{Grt} + \text{Cpx} + \text{Pl}_1 = \text{Opx} + \text{Pl}_2$ (for a description of the method, see also Braga *et al.*, 2005), in the realistic hypothesis that the M3 corona was mainly derived from reaction between mantle garnet and the clinopyroxene + plagioclase

Table 4. Representative SEM-EDS analyses of amphibole (EV02-42).

(Pl₁) symplectite after omphacite (Zhao *et al.*, 2001). The following compositions of reactants and products have been used:



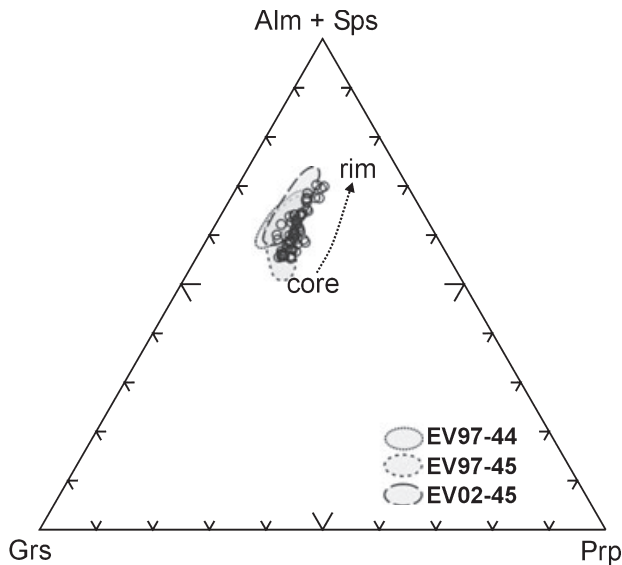


Fig. 5. Garnet compositions plotted in the (almandine + spessartine)-grossular-pyrope diagram. Garnet is zoned, showing an increase in Fe content (coupled with a decrease in grossular component) towards the rim.

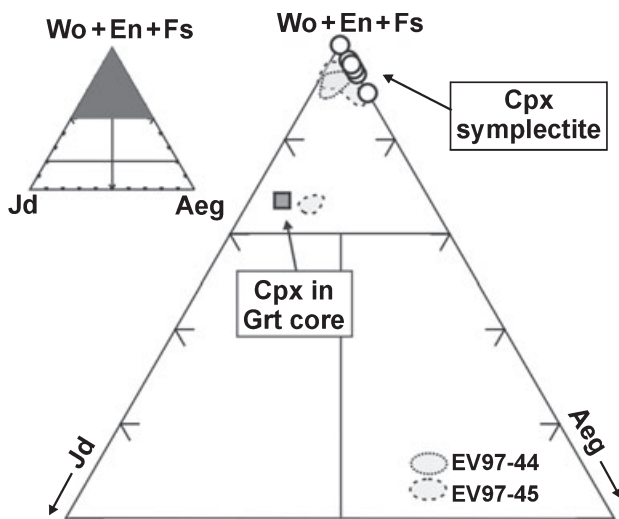
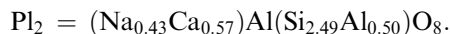
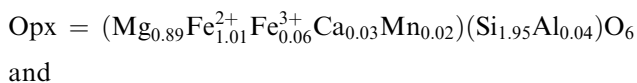
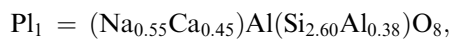


Fig. 6. Clinopyroxene compositions plotted in the (wollastonite + enstatite + ferrosilite)-jadeite-aegirine diagram of Morimoto (1988). Clinopyroxene inclusions in garnet core are locally enriched in the jadeite component, plotting in the diopside field close to omphacite, whereas clinopyroxene in the symplectite after omphacite is mainly a diopside.



The balanced reaction

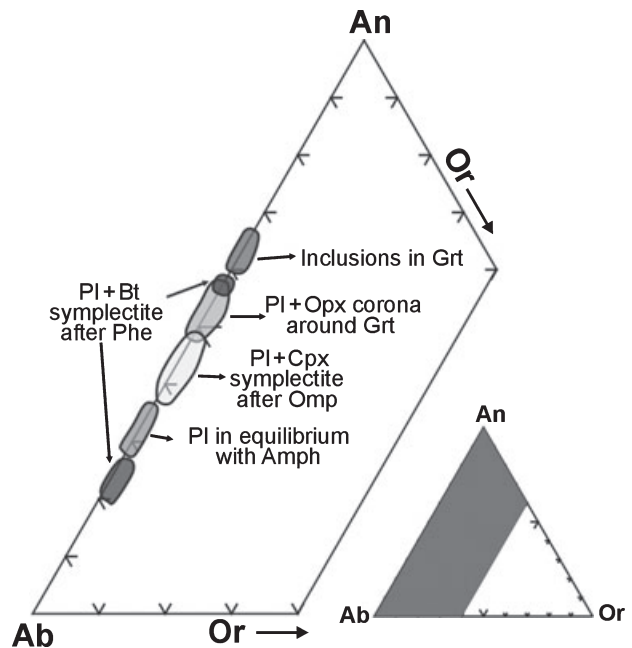


Fig. 7. Plagioclase compositions plotted in the albite-anorthite-orthoclase diagram. Plagioclase domains from different microstructural sites are characterized by different Ca contents. Plagioclase inclusions in garnet have the highest anorthite content, whereas the highest albite content has been detected in the core of plagioclase from the biotite + plagioclase symplectite after phengite.

gives the bulk-rock composition: $\text{Na}_2\text{O} = 4.69\%$, $\text{MgO} = 1.67\%$, $\text{Al}_2\text{O}_3 = 23.02\%$, $\text{SiO}_2 = 52.89\%$, $\text{CaO} = 10.91\%$, $\text{FeO} = 5.45\%$, $\text{Fe}_2\text{O}_3 = 1.20\%$, $\text{MnO} = 0.17\%$ (wt%), which was used to calculate pseudosection 2.

Both pseudosections were calculated following the approach of Connolly (1990) and using the internally consistent thermodynamic data set and equation of state for H_2O of Holland & Powell (1998, revised 2002). Because of the lack of suitable solid-solution models for the Fe^{3+} -bearing phases, all Fe^{3+} in the rock was used to create fictive magnetite, which is then stabilized in all the P - T fields, its modal amount being very low (6–7%). The effects of Fe^{3+} on the phase relations can be estimated qualitatively. As the substitution is most pronounced in clinopyroxene and amphibole, their stability fields will be slightly enlarged with the incorporation of Fe^{3+} in the solution models (Will *et al.*, 1998). The minerals considered in the calculation were: garnet, clinopyroxene, orthopyroxene, plagioclase, phengite, biotite, quartz, amphibole, zoisite, chlorite, rutile, titanite and ilmenite. Solid-solution models and mixing parameters used for garnet, omphacite, orthopyroxene, biotite, phengite, plagioclase, amphibole and chlorite are given in Table 5. Ilmenite solid solution has not been considered in the pseudosection calculations, because no relics of Mg-bearing geikelite-rich ilmenite have been observed in the studied samples. In both pseudosections, H_2O

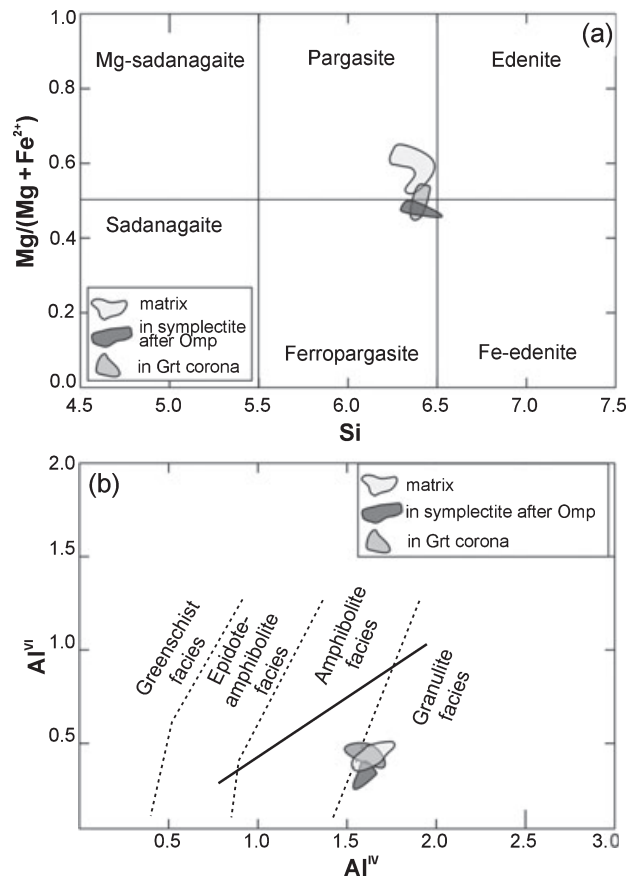


Fig. 8. (a) Classification diagram for Ca-amphibole in EV02-42 according to Leake *et al.* (1997). Brown amphibole in the matrix of the granulitized eclogite EV02-42 plots in the pargasite compositional field, whereas amphibole in the symplectite after omphacite and in the corona around garnet are mainly ferropargasite. (b) Amphibole compositions plotted in the Al^{VI} vs. Al^{IV} diagram. Low- P amphibole compositions (below solid line) and high- P amphibole compositions (above solid line) are differentiated, according to Raase (1974). Amphiboles from EV02-42 plot in the compositional field of amphibole from granulite-facies rocks (Zakrutkin, 1968) or at the transition between granulite- and amphibolite-facies amphiboles.

has been treated as a perfectly mobile component. Both pseudosections have been calculated at $a_{H_2O} = 1$ and at progressively reduced water activities. An

$a_{H_2O} = 1$ is unrealistic for the high- T granulite facies assemblages, whereas a reduced water activity for the granulitic stages is confirmed by a fluid-inclusion study (Ferrando *et al.*, 2006), which reports the occurrence of multisolid CO_2 -rich inclusions in garnet. This early CO_2 -dominated fluid was probably present during the granulitization stage, and was followed during decompression first by a mixed CO_2 - H_2O fluid and then by an aqueous fluid. In contrast, the choice of reduced water activity ($a_{H_2O} = 0.5$), is probably unrealistic for the eclogitic stage: the fluid inclusion study (Ferrando *et al.*, 2006), in fact, reports aqueous fluid inclusions preserved in the relict garnet cores. However, the effects of the water activity variation on the stability of the eclogite paragenesis was checked, by constructing a P vs. a_{H_2O} pseudosection at 800 °C (Fig. 11). This pseudosection clearly shows that the eclogitic assemblage is not influenced by the water activity, which was stable over the entire range of a_{H_2O} , from $a_{H_2O} = 0$ to 1 and that the granulitic paragenesis is stable at 800 °C for $a(H_2O) < 0.8$.

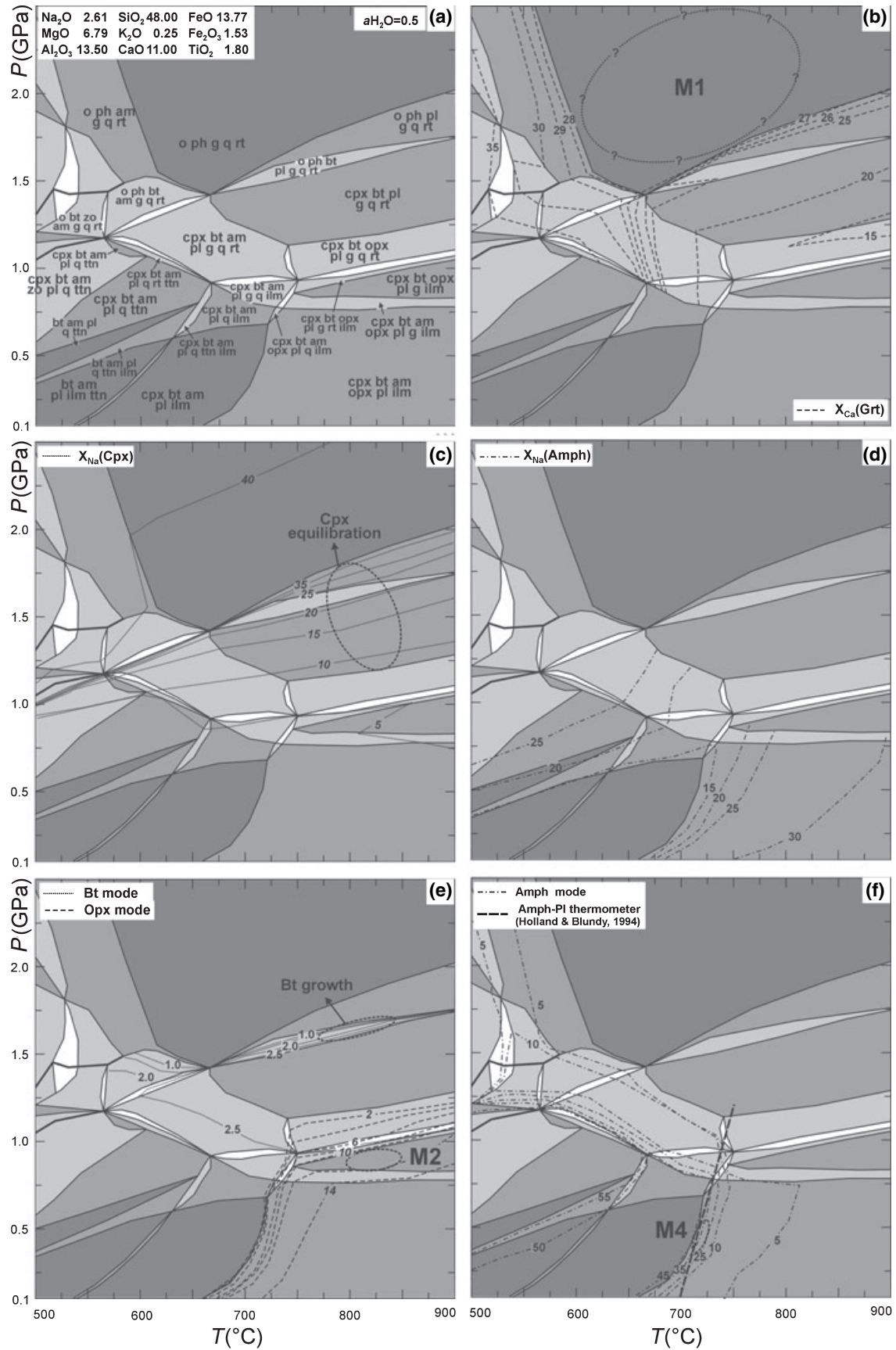
Results of pseudosection 1

The four metamorphic assemblages M1, M2, M3 and M4 were modelled by pseudosection 1 in the P - T range 0.1–2.5 GPa and 500–900 °C. The resulting P - T pseudosection consists of di-, tri-, four-, and five-variant fields, which are represented in Fig. 9 in white, light, medium grey and dark grey, respectively.

Eclogite M1 assemblage

The partially retrogressed eclogitic assemblage M1, consisting of garnet, omphacite, phengite, quartz and rutile, is modelled by a five-variant field at > 1.5 GPa and > 580 °C. The $X_{Ca}(Grt)$ [$X_{Ca}(Grt) = Ca/(Ca + Mg + Fe)$] isopleths in this field suggest that eclogitic garnet was characterized by $X_{Ca} = 0.27$ – 0.28 (Fig. 9b), which corresponds to the highest grossular content locally preserved in the core of larger garnet crystals (Table 1 & Fig. 5). The $X_{Na}(Cpx)$ [$X_{Na}(Cpx) = Na/(Na + Ca)$] modelled by the P - T pseudosection for the eclogite-facies stage ranges between 0.35 and 0.40 (Fig. 9c); no relics of omphacite with this jadeite

Fig. 9. (a) Pseudosection 1 for granulitized eclogite EV02-42 calculated at $a_{H_2O} = 0.5$ in the NKCFMASH + Ti system, using the bulk-rock composition given in the top left inset. Magnetite is stable in all the P - T fields. White, light grey, medium grey and dark grey fields are di-, tri-, quadri- and five-variant fields, respectively. Di-variant eight-phase assemblages, sharing phases of the adjacent tri-variant seven-phase fields, are not labelled for clarity (am = amphibole; bt = biotite; cpx = clinopyroxene; g = garnet; ilm = ilmenite; o = omphacite; opx = orthopyroxene; ph = phengite; pl = plagioclase; q = quartz; rt = rutile; ttn = titanite; zo = zoisite). (b) X_{Ca} [$Ca/(Mg + Fe + Ca) \times 100$] isopleths for garnet. The dotted ellipse shows the approximate P - T conditions for the M1 assemblage, as suggested by the $X_{Ca}(Grt)$ isopleths. (c) X_{Na} [$Na/(Na + Ca) \times 100$] isopleths for omphacite and clinopyroxene. The dashed ellipse represents the P - T field of omphacite-clinopyroxene equilibration during early decompression. (d) X_{Na} [$Na/(Ca + Na) \times 100$] isopleths for amphibole. (e) Modal isopleths of biotite and orthopyroxene. The dashed-line ellipses represent the P - T fields of biotite development during early retrogression and of M2 assemblage stability, as suggested by modal isopleths of biotite and orthopyroxene, respectively. (f) Modal isopleths of amphibole. The dashed line shows the results of the Holland & Blundy (1994) thermometer applied on the brown amphibole + plagioclase assemblage M4. The dashed ellipse shows the P - T conditions for the M4 assemblage stability, as suggested by modal and compositional isopleths of amphibole.



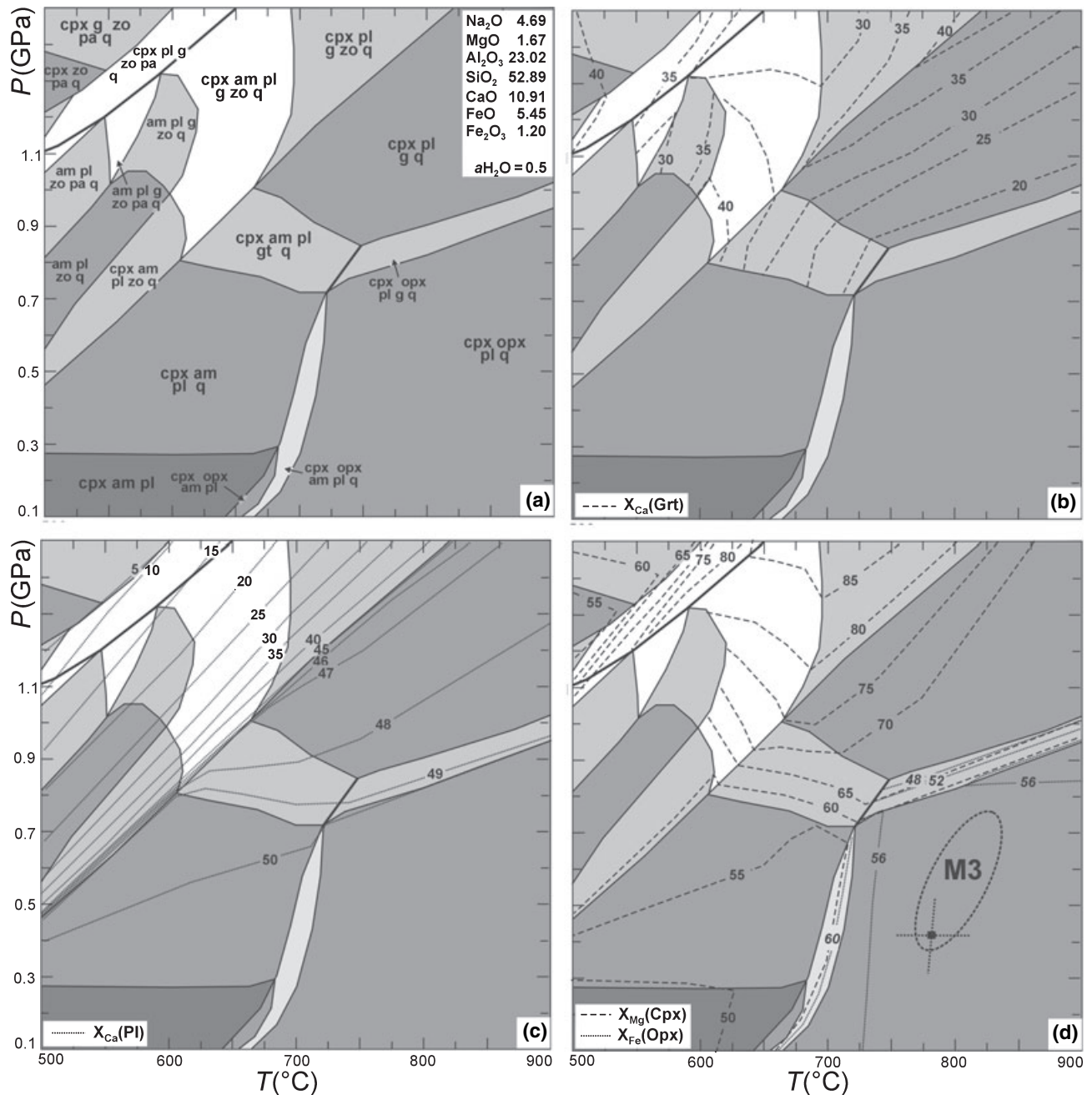


Fig. 10. (a) Pseudosection 2 calculated at $aH_2O = 0.5$ in the NCFMASH system, using the bulk composition (top right inset) obtained balancing the reaction $Grt + Cpx + Pl_1 = Opx + Pl_2$. Magnetite is stable in all the P - T fields. White, light grey, medium grey and dark grey fields are di-, tri-, quadri- and five-variant fields, respectively. (Mineral abbreviations as in Fig. 9a). (b) $X_{Ca}[Ca/(Ca + Fe + Mg) \times 100]$ isopleths for garnet. (c) $X_{Ca}[Ca/(Ca + Na) \times 100]$ isopleths for plagioclase. (d) $X_{Mg}[Mg/(Mg + Fe^{2+}) \times 100]$ isopleths for clinopyroxene and $X_{Fe}[Fe^{2+}/(Fe^{2+} + Mg) \times 100]$ isopleths for orthopyroxene. Dotted lines show the results of the clinopyroxene-orthopyroxene thermometer (Anderson *et al.*, 1993) and of the clinopyroxene-plagioclase-quartz barometer (Brandelik & Massonne, 2004). Dashed ellipse shows the P - T conditions for the M3 assemblage stability, as suggested by compositional isopleths of clinopyroxene and orthopyroxene.

content were observed. However, area analysis of the clinopyroxene + plagioclase symplectite, reported by Lombardo & Rolfo (2000) for similar granulitized eclogites, suggests jadeite contents ranging from 35 to 45 mol.%.

During the early decompression, at < 1.8 GPa (at a nominal 800 °C), $X_{Na}(Cpx)$ sharply decreases and a Na-rich plagioclase becomes stable (Fig. 9c). This marks the beginning of symplectite formation after omphacite: clinopyroxene in the symplectite is diop-

Table 5. Solid-solution models and mixing parameters used in the pseudosection calculations.

Phase solution models	End members	References
Omphacite (o) $\text{Na}_{1-x}\text{Ca}_x\text{Mg}_{1-y}\text{Fe}_{(1-x-y)}\text{Al}_y\text{Si}_2\text{O}_6$	Diopside Hedenbergite Jadeite	$\text{CaMgSi}_2\text{O}_6$ $\text{CaFeSi}_2\text{O}_6$ $\text{NaAlSi}_2\text{O}_6$ Holland & Powell (1996)
Garnet (g) $\text{Fe}_{3x}\text{Ca}_{3y}\text{Mg}_{3z}\text{Mn}_{3(1-x-y-z)}\text{Al}_2\text{Si}_3\text{O}_{12}$ $x + y + z < 1$	Spessartine Almandine Pyrope Grossular	$\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ Holland & Powell (1998)
Orthopyroxene (opx) $(\text{Mg}_x\text{Fe}_{1-x})_{2-y}\text{Al}_y\text{Si}_{2-y}\text{O}_6$	Enstatite Ferrosilite mg-tschermak fets_i = 1 mgts + 1 opx - 1 en	$\text{Mg}_2\text{Si}_2\text{O}_6$ $\text{Fe}_2\text{Si}_2\text{O}_6$ $\text{MgAl}_2\text{SiO}_6$ Holland & Powell (1996)
Phengite (Ph) $\text{K}_x\text{Na}_{1-x}\text{Mg}_y\text{Fe}_z\text{Al}_{3-2(y+z)}\text{Si}_{3+y+z}\text{O}_{10}(\text{OH})_2$	Celadonite Fe-celadonite Muscovite Paragonite	$\text{KMgAlSi}_4\text{O}_{10}(\text{OH})_2$ $\text{KFeAlSi}_4\text{O}_{10}(\text{OH})_2$ $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$ $\text{NaAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$ Holland & Powell (1998)
Amphibole (am) $\text{Ca}_{2-2w}\text{Na}_z + 2w[\text{Mg}_x\text{Fe}_{1-x}]_3 + 2y + z\text{Al}_{3-3y-w}\text{Si}_{7+w+y}\text{O}_{22}(\text{OH})_2$ $w + y + z < 1$	Tremolite Fe-actinolite Pargasite Tschermakite Glaucophane fparg_d = 1 parg + 4/5 ftr - 4/5 tr fts_d = 1 ts + 3/5 ftr - 3/5 tr fgl_d = 1 gl + 3/5 ftr - 3/5 tr	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ $\text{NaCa}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{22}(\text{OH})_2$ $\text{Ca}_2\text{Mg}_3\text{Al}_4\text{Si}_6\text{O}_{22}(\text{OH})_2$ $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ Dale <i>et al.</i> (2005)
Plagioclase (pl) $\text{Na}_x\text{Ca}_{1-x}\text{Al}_{2-x}\text{Si}_2+x\text{O}_8$	Albite Anorthite	$\text{NaAlSi}_3\text{O}_8$ $\text{CaAl}_2\text{Si}_2\text{O}_8$ Newton <i>et al.</i> (1981)
Biotite (bt) $\text{KMg}_{(3-w)}\text{Fe}_{(3-w)}\text{Mn}_{(3-w)(1-x-y)}\text{Al}_1 + 2w\text{Si}_{3-y+z}\text{O}_{10}(\text{OH})_2$ $x + y < 1$	Annite Eastonite Mn-biotite Phlogopite mnts_i = 1 east + 2/3 mnbi - 2/3 phe sdph_i = 1 east + 2/3 ann - 2/3 phl	$\text{KFe}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ $\text{KMg}_2\text{Al}_3\text{Si}_2\text{O}_{10}(\text{OH})_2$ $\text{KMn}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ $\text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ Powell & Holland (1999)
Chlorite (ch) $\text{Mg}_{(5-y+z)}\text{Fe}_{(5-y+z)}\text{Mn}_{(5-y+z)(1-x-w)}\text{Al}_2(1+y+z)\text{Si}_{3-y+z}\text{O}_{10}(\text{OH})_8$ $x + w < 1$	Clinocllore Daphnite Mn-chlorite	$\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_4$ $\text{Fe}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_4$ $\text{Mn}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_4$ Holland <i>et al.</i> (1998)

mnts = Mn-tschermak; east = eastonite; mnbi = Mn-biotite; phe = phlogopite; sdph = siderophyllite; ann = annite

fparg = Fe-pargasite; parg = pargasite; ftr = Fe-tremolite; tr = tremolite; fts = Fe-tschermakite; ts = tschermakite; fgl = Fe-glaucophane; gl = glaucophane.

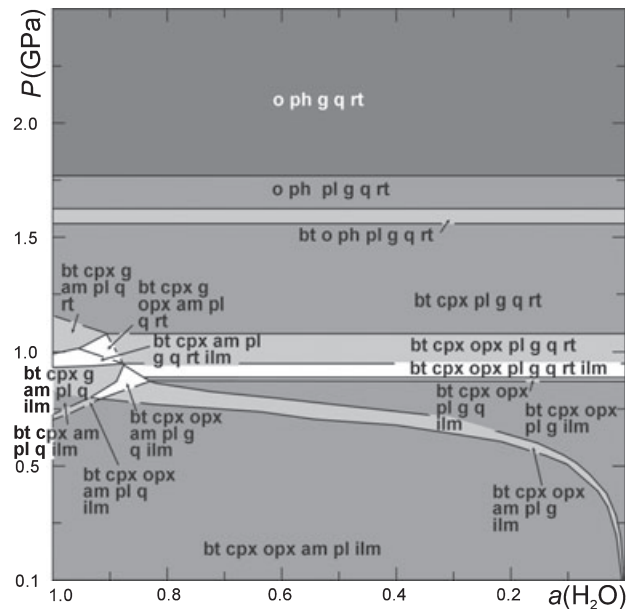


Fig. 11. P - $a(\text{H}_2\text{O})$ pseudosection for granulitized eclogite EV02-42 calculated at 800 °C in the NCKFMASH + Ti system. Magnetite is stable in all the P - T fields. White, light grey, medium grey and dark grey fields are di-, tri-, quadri- and five-variant fields, respectively. (Mineral abbreviations as in Fig. 9a).

side (Table 2 & Fig. 6), suggesting that clinopyroxene continuously re-equilibrated during decompression down to $X_{\text{Na}}(\text{Cpx}) < 0.05$ (i.e. down to < 1.0 GPa). At < 1.7 GPa (at a nominal 800 °C), biotite becomes stable and progressively replaces phengite by forming the biotite + plagioclase symplectite. The modal isopleths of biotite indicate that it mainly grew at ~ 1.5 – 1.6 GPa, i.e. during the early decompression from eclogite to granulite facies (Fig. 9e).

Thermal peak assemblage M2

Although orthopyroxene first becomes stable at < 1.2 GPa (at a nominal 800 °C), the peak assemblage M2, consisting of garnet, clinopyroxene, orthopyroxene, plagioclase and ilmenite is modelled by the four-variant field $\text{Cpx} + \text{Opx} + \text{Grt} + \text{Pl} + \text{Qtz} + \text{Bt} + \text{Ilm}$ at 0.8–1.0 GPa and > 750 °C (Fig. 9a). Pressure conditions are particularly well constrained by the presence of ilmenite (instead of rutile) and by the absence of quartz in the peak-temperature paragenesis. Quartz was consumed by the symplectite-producing reaction: $\text{Omph} + \text{Qtz} = \text{Na-Cpx} + \text{Pl}$ (Heinrich, 1982; O'Brien, 1989; Rubie,

1990; Smelov & Beryozkin, 1993; Möller, 1998), as also indicated by the modal isopleths of quartz, which show the decrease of the modal content of quartz from the eclogitic stage down to the granulitic stage. Quantitative considerations may be inferred using the compositional isopleths of garnet and clinopyroxene and the modal isopleths of orthopyroxene. The measured $X_{Ca}(Grt) = 0.17\text{--}0.23$ in the inclusion-free mantle of garnet and $X_{Na}(Cpx) < 0.05$ in the matrix-type clinopyroxene are consistent with the trend of isopleths in pseudosection 1 (Fig. 9b,c). Furthermore, the modal isopleths of orthopyroxene suggest that it mainly grew at pressures between 0.8 and 1.0 GPa (Fig. 9e), which are consistent with the modelled pressure conditions for the granulitic peak. As the compositional isopleths of both garnet and clinopyroxene are only pressure-dependent, the temperature conditions for the peak M2 assemblage cannot be more tightly constrained.

Retrograde M3 assemblage (plagioclase + orthopyroxene ± amphibole corona around garnet)

The plagioclase + orthopyroxene ± amphibole corona that developed at the expense of garnet is modelled by the large four-variant $Cpx + Opx + Pl + Bt + Amph + Ilm$ field, which occurs at pressures lower than 0.8 GPa (Fig. 9a). Quantitative data for the granulitic corona around garnet will be discussed later and are inferred from pseudosection 2 (Fig. 10), calculated using the effective bulk composition of the micro-domain involved in the reaction.

Retrograde M4 assemblage (brown amphibole + plagioclase)

Although amphibole becomes stable at ~0.8 GPa and at >740 °C (i.e. in the four-variant field $Cpx + Opx + Pl + Bt + Amph + Ilm$), modal isopleths of amphibole suggest that it mainly grew at <740 °C, approximately at the boundary between the four-variant field $Cpx + Opx + Pl + Bt + Amph + Ilm$ and the five-variant field $Cpx + Pl + Bt + Amph + Ilm$ (Fig. 9f). $X_{Na}(Amph)$ [$X_{Na}(Amph) = Na/(Na + Ca)$] isopleths at <740 °C are consistent with the measured compositions, which have $X_{Na}(Amph) = 0.18\text{--}0.21$ (Fig. 9d).

The hornblende-plagioclase thermometer (Holland & Blundy, 1994) applied to matrix-type brown amphibole and plagioclase ($X_{An} = 0.31$) confirms the results of the P – T pseudosection, suggesting 713 °C at 0.4 GPa and 722 °C at 0.6 GPa, respectively (Fig. 9f). The good agreement between the modelled modal and compositional isopleths (obtained using a Fe^{3+} -free amphibole solution model) and the hornblende-plagioclase thermometer (which involves Fe^{3+} in amphibole) suggests that the effects of Fe^{3+} introduction in amphibole are negligible.

Results of pseudosection 2

Pseudosection 2, calculated in the P – T range 0.1–1.5 GPa and 500–900 °C using the effective bulk composition previously discussed, was used to quantitatively model the second granulitic stage represented by the corona of plagioclase + orthopyroxene ± amphibole around garnet. Pseudosection 2 is dominated by tri- and four-variant fields, with minor di-variant fields (Fig. 10).

The reactants of the reaction (1) are modelled by the four-variant $Cpx + Pl + Grt + Qtz$ field at pressures above 0.8 GPa, whereas the products are stabilized in the four-variant field $Cpx + Pl + Opx + Qtz$ at $P < 0.8$ GPa. Mantle garnet used to balance the reaction is characterized by an average $X_{Ca}(Grt) = 0.21$, whereas clinopyroxene and plagioclase of the symplectite after omphacite have average $X_{Mg}(Cpx) = 0.67$ and $X_{Ca}(Pl) = 0.43$. The modelled $X_{Ca}(Grt)$, $X_{Mg}(Cpx)$ and $X_{Ca}(Pl)$ isopleths show that the reactant assemblage was stable at 0.9–1.0 GPa and >740 °C (Fig. 10b–d). The average $X_{Ca}(Pl) = 0.52$ and $X_{Fe}(Opx) = 0.56$ of the reaction products are modelled by the respective isopleths at <0.8 GPa and >700 °C (Fig. 10c,d). Since $X_{Ca}(Pl)$ and $X_{Fe}(Opx)$ are essentially P -dependent at $T > 740$ °C, tighter temperature constraints cannot be inferred from pseudosection 2.

Independent P – T conditions for the second granulitic stage were inferred by using conventional thermobarometry applied to clinopyroxene, orthopyroxene and plagioclase stably coexisting in the symplectite after omphacite. Conditions of 783 °C and 0.41 GPa are indicated by the intersection between the clinopyroxene-orthopyroxene thermometer (obtained using the QUILF program of Anderson *et al.*, 1993) and the clinopyroxene-plagioclase-quartz barometer (Brandelik & Massonne, 2004) (Fig. 10d). These P – T conditions are plotted in the four-variant $Cpx + Opx + Pl + Qtz$ field modelled by pseudosection 2 and provide tighter constraints for the second granulitic stage.

GARNET-BIOTITE-SILLIMANITE GNEISS

In order to better constrain the last portion of the P – T path reconstructed on the basis of the mafic granulite paragenesis and mineral compositions, a garnet-biotite-sillimanite gneiss (sample EV97-60) was also studied using two different approaches: modelling of phase equilibria by a calculated petrogenetic grid and conventional thermobarometry. Gneiss EV97-60 crops out in the Ama Drime range (Fig. 1), close to eclogite EV 97-44 described by Lombardo & Rolfo (2000), and its protolith is a metapelitic intercalation inside the country rock granitic orthogneisses hosting the granulitized eclogites. The relatively simple mineralogy of the hosting orthogneisses cannot precisely constrain their metamorphic

evolution: on the contrary, the more reactive metapelitic intercalations, consisting of garnet, biotite and sillimanite, allow the application of conventional thermobarometry in order to constrain the later portion of their P - T path.

Sample EV97-60 is a foliated rock mainly consisting of biotite + sillimanite layers, which define the main schistosity, alternating with lensoidal quartz + plagioclase-rich domains (Fig. 12a). No relics of the eclogitic paragenesis are preserved, but plagioclase locally contains small kyanite inclusions (Fig. 12b), which are relics of a higher pressure metamorphic assemblage (>1.0 GPa at nominal 800 °C). Kyanite is not preserved in the rock matrix, which shows mats of fibrolitic sillimanite instead. Small garnet crystals appear to be in equilibrium with biotite (Fig. 12a).

Following the approach of Borghi *et al.* (2003) for metapelites of the Kharta Gneiss Complex, P - T conditions for the biotite + sillimanite + plagioclase + garnet paragenesis were estimated using thermodynamic modelling of phase equilibria. A petrogenetic grid was calculated in the model KFMASH system according to the method of Connolly (1990) and by using the internally consistent data set and equation of state for H_2O (Holland & Powell, 1998, revised 2002). SiO_2 , Al_2O_3 and $KAlO_2$ components were considered in excess, so that the system is always saturated with respect to quartz, an Al_2SiO_5 polymorph and muscovite or K-feldspar depending on temperature. H_2O was treated as a perfectly mobile component. The phases considered in the calculation were: biotite (phl, ann), chlorite (clinochlore, daphnite), chloritoid (Mg-ctd, Fe-ctd), cordierite (Mg-crd, Fe-crd), garnet (prp, alm), K-feldspar, muscovite, quartz, spinel (spl, hrc), staurolite (Mg-st, Fe-st) and the Al_2SiO_5 polymorphs (mineral abbreviations according to Bucher & Frey, 2002). Solid-solution models used in the calculation were taken from Holland & Powell (1998) for garnet,

staurolite, chloritoid and spinel, Holland *et al.* (1998) for chlorite, Powell & Holland (1999) for biotite. An ideal solution model was used for cordierite. The resulting petrogenetic grid (Fig. 13) is similar to that reported in Borghi *et al.* (2003); minor shifts in the location of the equilibrium curves are due to the use of both improved (biotite) and extended (chlorite) solution models. The sillimanite + biotite + garnet paragenesis is modelled by the two-phase assemblage Grt + Bt (saturated phases omitted) occurring at >600 °C and >0.3 GPa. The calculated pseudo-univariant equilibria between garnet and biotite allowed to estimate P - T conditions for the studied paragenesis. The shaded oval in Fig. 13, localized at ~ 675 °C and ~ 0.43 GPa, represents the P - T field where discrepancies between the predicted and measured mineral compositions are minimal.

The P - T conditions for the biotite + sillimanite + plagioclase + garnet assemblage were independently estimated using the conventional biotite-garnet thermometer and the GASP barometer compiled by D.J. Waters (spreadsheet 'pelite.barometers.xls' at: http://www.earth.ox.ac.uk/~davewa/pt/th_tools.html). P - T conditions of 651 °C and 0.44 GPa are indicated by the intersection between the Bt-Grt thermometer of Bhattacharya *et al.* (1992) and the GASP barometer applied on core compositions of garnet, plagioclase and biotite (Table 6). Lower P - T estimates (627 °C and 0.31 GPa) were inferred using rim compositions of garnet, plagioclase and biotite (Table 6).

Such thermobarometric data, reported in Fig. 13, are consistent with the equilibrium conditions derived from the calculated KFMASH petrogenetic grid (~ 0.43 GPa, ~ 675 °C; Fig. 13). Moreover, P - T conditions estimated for the biotite + sillimanite + plagioclase + garnet assemblage in the gneiss, are in very good agreement with the P - T data obtained from

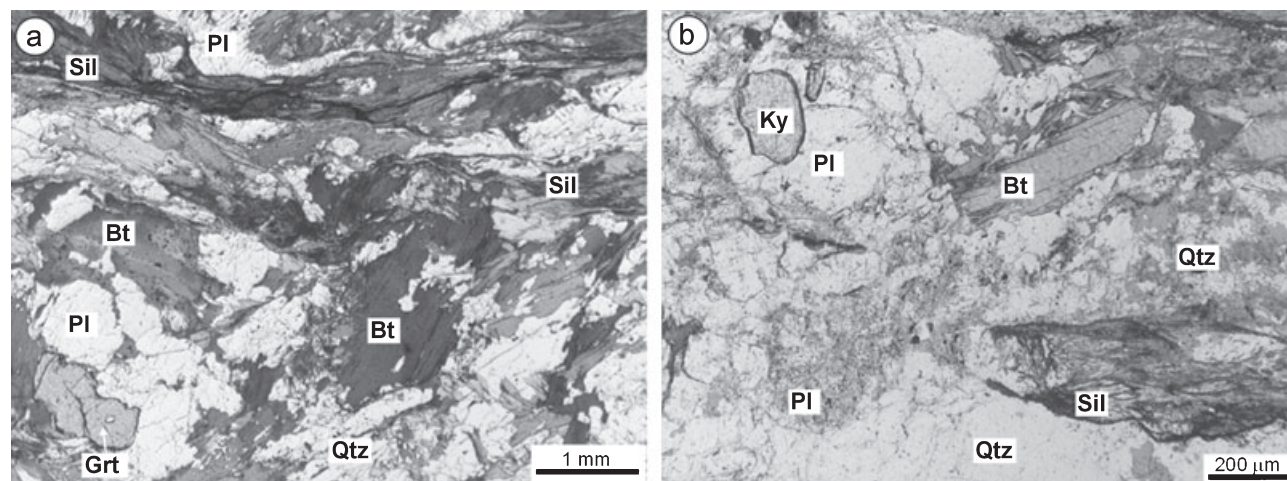
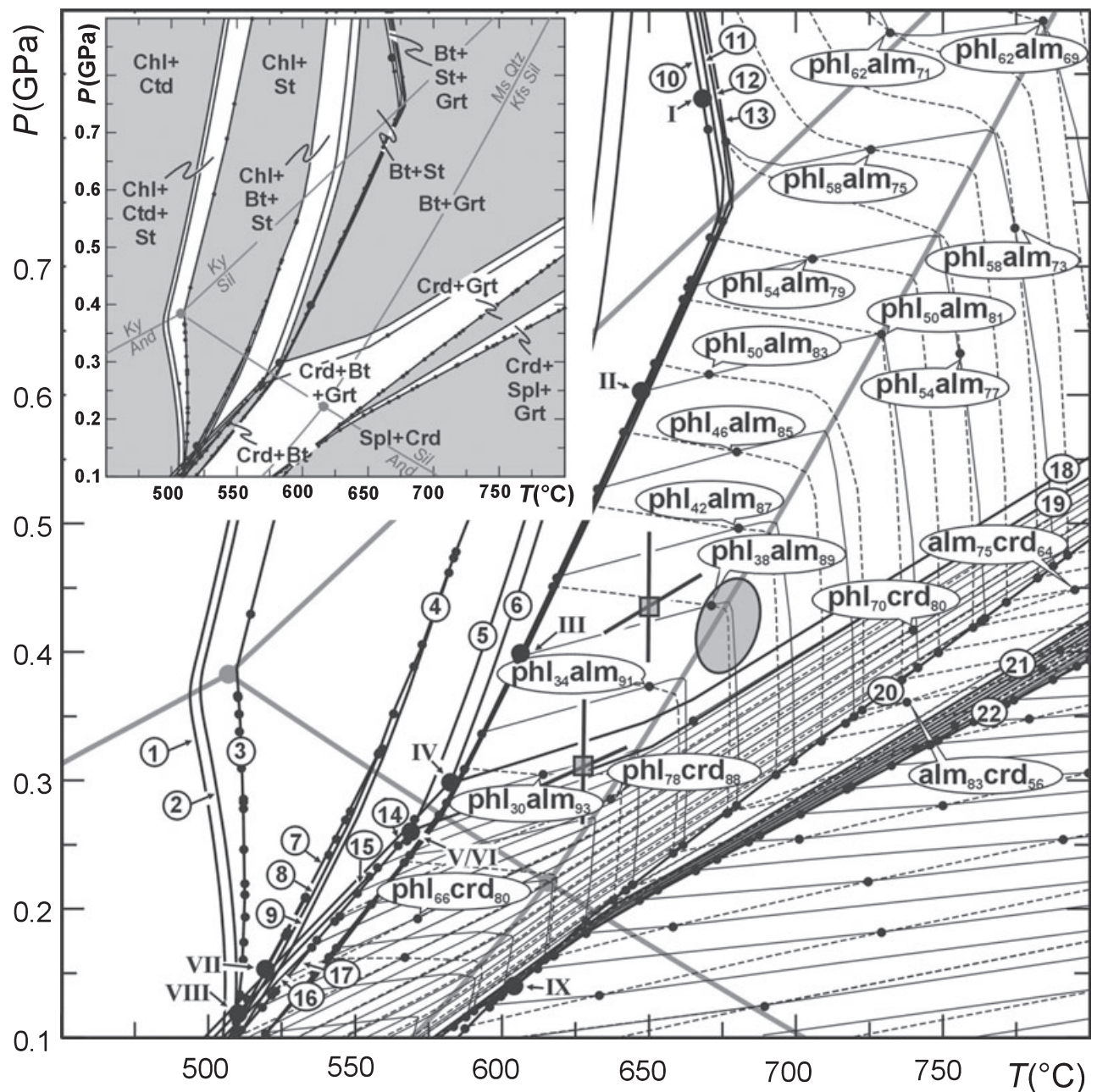


Fig. 12. Microstructure of the biotite-garnet-plagioclase-sillimanite gneiss EV97-60. (a) Biotite (Bt) + sillimanite (Sil) layers, which define the main schistosity, alternating with lensoidal quartz (Qtz) + plagioclase (Pl)-rich domains and rare garnet (Grt) crystals. (b) Relict kyanite (Ky) inclusions in plagioclase (Pl) and fibrolitic sillimanite (Sil) in the rock matrix.



UNIVARIANT REACTIONS

- | | |
|---|---|
| (1) Fe-Ctd ALS = Fe-St Qtz | (12) Bt _{ss} St _{ss} Qtz = Grt _{ss} ALS Ms |
| (2) Ctd _{ss} ALS = St _{ss} Qtz | (13) Fe-St = Alm |
| (3) Ctd _{ss} ALS = Chl _{ss} St _{ss} Qtz | (14) Mg-Chl Qtz ALS = Crd |
| (4) Chl _{ss} St _{ss} Ms = Bt _{ss} Qtz ALS | (15) Chl _{ss} Qtz ALS = Crd _{ss} |
| (5) Chl _{ss} Ms = Bt _{ss} Qtz ALS | (16) Chl _{ss} Qtz Ms = Crd _{ss} Bt _{ss} ALS |
| (6) Mg-Chl Ms = Phl Qtz ALS | (17) Chl _{ss} Qtz ALS Ms = Crd _{ss} Bt _{ss} |
| (7) St _{ss} Chl _{ss} Ms = Bt _{ss} Qtz ALS | (18) Phl Qtz ALS = Crd Ms |
| (8) Chl _{ss} Ms = Bt _{ss} Qtz ALS | (19) Bt _{ss} Qtz ALS = Crd _{ss} Ms |
| (9) Chl _{ss} Ms = Bt _{ss} Qtz ALS | (20) Bt _{ss} Qtz ALS = Grt _{ss} Crd _{ss} Kfs |
| (10) Bt _{ss} St _{ss} Qtz = Grt _{ss} ALS Ms | (21) Alm ALS = Hc Qtz |
| (11) Bt _{ss} St _{ss} Qtz = Grt _{ss} ALS Ms | (22) Grt _{ss} ALS = Crd _{ss} Spl _{ss} Qtz |

INVARIANT ASSEMBLAGES

- | |
|--|
| (I) Phl ₂₀ St ₁₉ St ₂₂ Alm ₇₈ |
| (II) St ₂₆ St ₂₃ Phl ₅₃ Alm ₈₄ |
| (III) St ₁₀ Phl ₄₀ St ₇ Alm ₉₀ |
| (IV) Mg-Chl Phl ₉₆ St ₇ Alm ₉₀ |
| (V) Chl ₉₂ Crd Phl ₉₂ Crd ₉₂ |
| (VI) Crd ₉₂ Phl ₈₈ Chl ₉₂ Phl ₉₂ |
| (VII) Phl ₃₂ St ₄ Phl ₂₈ Chl ₂₈ |
| (VIII) St ₄ Chl ₂₈ Crd ₆ Phl ₂₄ |
| (IX) Alm ₉₆ Phl ₂₀ Crd ₂₈ Spl ₄ |

Table 6. Representative SEM-EDS analysis of selected minerals from the Grt-Sil gneiss (EV97–60).

Point analysis	Garnet		Biotite			Plagioclase		
	SIGRT 10	SIGRT1	S1BT2.1	S1BT1.3	S1PL2.1	S2PL1.1		
	Core	Rim	Core	Rim	Core	Rim		
SiO ₂	36.40	35.10	SiO ₂	33.34	33.80	SiO ₂	59.71	58.29
Al ₂ O ₃	19.94	19.64	TiO ₂	1.80	0.71	Al ₂ O ₃	23.12	24.37
FeO _{tot}	36.87	35.75	Al ₂ O ₃	18.20	19.24	CaO	6.21	7.96
MnO	1.87	3.15	FeO _{tot}	21.12	23.07	Na ₂ O	7.80	7.05
MgO	2.86	2.40	MgO	6.91	6.92	K ₂ O	0.00	0.00
CaO	1.54	1.34	Na ₂ O	0.00	0.00	Total	96.84	97.66
Total	99.48	97.39	K ₂ O	9.61	9.64			
			Total	90.98	93.38			
Si	2.98	2.96	Si	2.70	2.69	Si	2.74	2.66
Al	1.93	1.95	Al ^{IV}	1.30	1.31	Al	1.25	1.31
Fe ²⁺ _{tot}	2.53	2.52	Al ^{VI}	0.44	0.49	Ca	0.30	0.39
Mn	0.13	0.22	Ti	0.11	0.04	Na	0.69	0.62
Mg	0.35	0.30	Fe ²⁺ _{tot}	1.43	1.53	K	0.00	0.00
Ca	0.14	0.12	Mg	0.83	0.82			
			Na	0.00	0.00			
			K	0.99	0.98			

the granulitized eclogite, and allow the last portion of the exhumation history of the unit to be better constrained.

DISCUSSION

Contrasting *P–T* evolution of LHCS and GHS in the Kharta region

Four main metamorphic stages have been recognized in the granulitized eclogite from the LHCS of the Ama Drime Range on the basis of microstructural data, quantitative *P–T* pseudosection analysis and conventional thermobarometry.

M1

This is the first stage, occurring under eclogite facies conditions, characterized by the assemblage garnet + omphacite + phengite + quartz + rutile. Because of the rare occurrence of eclogitic mineral relics, this stage may be only loosely constrained at >1.5 GPa and >580 °C by phase relations (stability of garnet, phengite and omphacite) and garnet-core composition (Figs 9b & 14). Similar *P–T* conditions were hypothesized by Lombardo & Rolfo (2000) for eclogites south-east of Kharta. During the decompression following the high-pressure peak, biotite + plagioclase and clinopyroxene + plagioclase symplectites devel-

oped after phengite and omphacite, respectively. Modal isopleths of biotite and compositional isopleths of clinopyroxene suggest that the biotite + plagioclase symplectite mainly developed in the narrow pressure range 1.5–1.6 GPa (Fig. 9e), whereas the symplectite after omphacite began to form at <1.8 GPa and clinopyroxene progressively re-equilibrated during the following decompression, finally reaching diopsidic compositions (Figs 9c & 14).

M2

The peak thermal assemblage consists of garnet, clinopyroxene, orthopyroxene, plagioclase and ilmenite. Phase relations (lack of quartz and stability of ilmenite instead of rutile) and compositional and modal isopleth contours tightly constrain the peak granulitic stage in the pressure range 0.8–1.0 GPa at >750 °C (Figs 9e & 14). The presence of a CO₂-rich fluid during this granulitic stage, shown by a fluid-inclusion study (Ferrando *et al.*, 2006), suggests a reduced water activity.

M3

During the subsequent exhumation, a second granulitic stage occurred at lower pressures, when plagioclase + orthopyroxene coronas developed around garnet. Thermobarometric data and *P–T* pseudosec-

Fig. 13. Petrogenetic grid calculated for the KFMASH system after projection through SiO₂, Al₂O₃ and KAlO₂. In the top left inset the stability fields of two-phase and three-phase assemblages (saturated phases omitted for clarity) are represented in dark and light grey, respectively (mineral abbreviations according to Bucher & Frey, 2002). Univariant curves, involving either end members or solution phases are reported as thick-solid curves. Small full dots along univariant curves are pseudo-invariant points deriving from the pseudocompound approximation (Connolly & Kerrick, 1987); large dots are true invariant points. Thin-solid and thin-dashed curves are pseudo-univariant assemblages, corresponding to isopleths of biotite and cordierite, and of garnet and spinel solid solutions, respectively. Representative pseudo-invariant assemblages along pseudo-univariant curves are labelled with averaged compositions of solid solutions. Reactions involving only the saturated phases are shown as dark grey curves. ALS is the Al₂SiO₅ polymorph stable at appropriate *P–T* conditions. The shaded oval represents the *P–T* field where minimal discrepancies exist between the predicted and observed mineral compositions. The thick solid lines intersecting at small grey squares represent the thermobarometric estimates derived from the garnet-biotite thermometer (Bhattacharya *et al.*, 1992) and GASP barometer.

tion analysis suggest average equilibration at 783 °C at 0.41 GPa (Figs 10d & 14).

M4

After the M3 stage, eclogite EV02-42 remained at metamorphic pressure of ~0.4 GPa, but experienced significant cooling to almost 700 °C, with the appearance of brown amphibole and plagioclase in the matrix. Modal and compositional isopleths of amphibole suggest that it formed at < 740 °C (Figs 9f & 14). The P - T conditions inferred from the host gneiss extend the P - T trajectory down to ~630 °C and ~0.3 GPa (Figs 13 & 14).

In conclusion, the combination of petrographic textures, mineral compositions, pseudosection analysis and thermobarometric data from the Ama Drime eclogite and host garnet-biotite-sillimanite gneiss defines a clockwise P - T path as summarized in

Fig. 14. It differs from the P - T path reported by Lombardo & Rolfo (2000) mainly for the slightly higher-pressure conditions suggested for the eclogitic M1 assemblage and for the identification of two distinct granulitic assemblages, one at higher pressures (M2) and one at lower pressures (M3). This detailed P - T path puts tight constraints on the exhumation history of the eclogite, which was characterized first by a decompression from ~2.0 GPa to ~0.4 GPa, followed by nearly isobaric cooling from ~775 °C to ~630 °C.

The P - T path of the GHS, as calculated from the Kharta Gneiss Complex on the basis of petrographic evidence, geothermobarometric estimates and calculated phase relations (Borghini *et al.*, 2003) is characterized by a nearly isothermal decompression from > 0.7–0.8 GPa to ~0.3 GPa, followed by a nearly isobaric cooling from ~710 °C to ~600 °C, at ~0.3 GPa (Fig. 14).

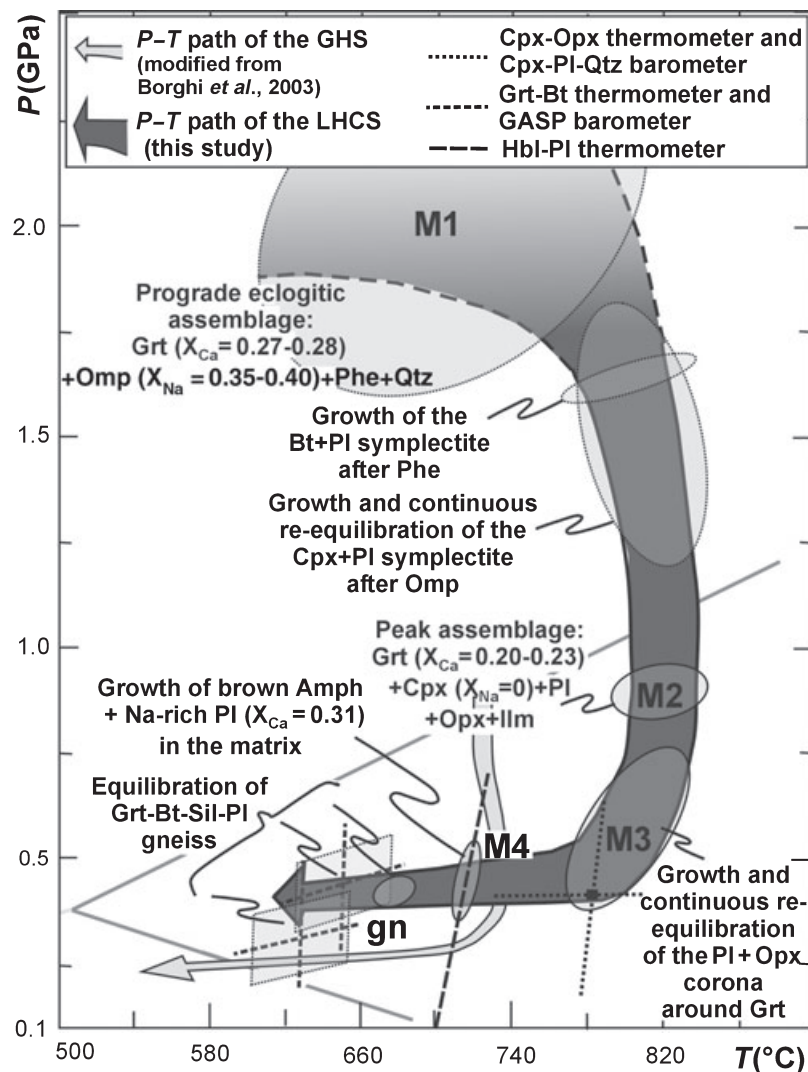


Fig. 14. P - T path for the LHCS from the granulitized eclogite EV02-42 of the Ama Drime Range. P - T estimates for the second granulitic stage M3, obtained using the Cpx-Opx thermometer and Cpx-Pl-Qtz barometer of Brandelik & Massonne (2004), are shown as dotted lines; temperature estimates for the amphibole + plagioclase assemblage, inferred on the basis of the Holland & Blundy (1994) thermometer, are shown as a long dashed line. Shaded ellipses show the P - T conditions for M1 assemblage stability, early decompressional biotite growth, clinopyroxene equilibration, and stability of M2, M3 and M4 assemblages, as derived from the compositional and modal isopleths modelled in pseudosection 1 and pseudosection 2 (Fig. 9b,c,e,f & 10d). P - T data derived from the biotite + plagioclase + sillimanite + garnet host gneiss (Grt-Bt thermometer of Bhattacharya *et al.*, 1992 and GASP barometer) are represented as short dashed lines, whereas those obtained on the basis of the petrogenetic grid (Fig. 13) are reported by the shaded oval labelled as 'gn'. The P - T path of the Kharta Gneiss Complex (GHS), modified from Borghi *et al.* (2003) is also shown.

The different P - T paths of LHCS and GHS confirm the field evidence suggesting that, in the area between Mt Everest and the Ama Drime Range, the metamorphic crystalline core of the Himalaya consists of two superposed units of high metamorphic grade. The lower unit, which we ascribe to the LHCS, essentially consists of granitic gneisses and is characterized by granulitized eclogites. The higher unit (Khartar Gneiss Complex), identical to the GHS of the Everest region and middle Arun Valley, is lithologically more varied, with a metasedimentary sequence intruded by Lower Palaeozoic and Proterozoic granites, and is characterized by relict medium- P granulite-facies mineral assemblages formed at metamorphic temperatures lower by ~ 80 °C than in the LHCS. Both units, after experiencing isothermal decompression at high- T , have isobarically cooled at low- P (~ 0.4 GPa for the LHCS and ~ 0.3 GPa for the GHS).

The existence of two lithotectonic units in the metamorphic core of the Himalaya instead of a single GHS, as generally admitted, is not exceptional. A particularly well-documented example is the Sutlej Valley area of Himachal Pradesh, India (Vannay *et al.*, 2004, and references therein), where both units show inverted metamorphic field gradients from garnet to sillimanite grade. In the Sutlej Valley the GHS experienced Early Miocene peak metamorphic conditions followed by Early to Middle Miocene rapid exhumation along the MCT II, whereas the LHCS underwent Late Miocene peak metamorphic conditions followed by rapid exhumation along the MCT I (Munsiari Thrust of Baudraz *et al.*, 2004).

The timing of tectonic processes involved in the metamorphism and exhumation of the LHCS in the Kharta region is hampered by the lack of precise time constraints on both the eclogitic M1 and granulitic M2 stages. Rolfo *et al.* (2005) dated zircon in eclogite EV02-45 from Tanghyu Valley by the U-Pb SHRIMP method. Ages ranging from 88 to 110 Ma, prevailing in the zircon cores, have been interpreted to represent a Cretaceous protolith age of the mafic rock. Such an age rules out the possibility that the age of eclogitization is Palaeozoic or Precambrian, and supports a Tertiary age for eclogitization in the Kharta region (Lombardo & Rolfo, 2000). The analysed zircon also shows very thin rims with low Th/U ratios (0.02–0.03), yielding young $^{206}\text{Pb}/^{238}\text{U}$ ages (12–15 Ma). The growth of these zircon rims could result from breakdown of garnet to orthopyroxene + plagioclase (Fraser *et al.*, 1997), and thus date the M3 stage. Alternatively, but less likely in view of the observation that hornblende is a potentially large sink for Zr (Fraser *et al.*, 1997), the zircon ages could be coeval with the amphibolite-facies metamorphism (M4 stage) and with fluid circulation linked to leucogranite emplacement along the MCT II at about 13 Ma (Liu *et al.*, 2005). Young $^{206}\text{Pb}/^{238}\text{U}$ ages (17.6 ± 0.3 Ma) were also found by Li *et al.* (2003) with the SHRIMP U-Pb method on zircon from a high-pressure mafic

granulite (actually a granulitized eclogite) of the northern Ama Drime Range.

Exhumation of Himalayan eclogites

New data on Kaghan and Tso Moriri eclogites and the data presented in this paper allow a closer comparison between the different Himalayan eclogites than that attempted by Lombardo & Rolfo (2000).

In the Tso Moriri eclogites, a first stage of decompression from > 750 °C and > 3.9 GPa (Mukherjee *et al.*, 2003) to ~ 600 °C at 2.0 GPa, still in the eclogite field was followed by isothermal decompression to 580 ± 60 °C, 1.1 ± 0.3 GPa (blueschist-amphibolitic stage) and 610 ± 80 °C, 0.9 ± 0.3 GPa (amphibolitic stage) according to estimates by De Sigoyer *et al.* (1997).

A similar P - T path, characterized by decompression under decreasing temperatures, was observed in the Kaghan eclogites, where the growth of porphyroblastic barroisite or glaucophane at the expense of omphacite marks early decompression in the eclogite field (Lombardo *et al.*, 2000; O'Brien *et al.*, 2001). Evidence of further decompression is given by the occurrence of amphibole + albite symplectite after omphacite and of biotite + feldspar replacing phengite (Lombardo *et al.*, 2000). The greenschist-facies overprint resulted in the growth of actinolitic amphibole, plagioclase and titanite. Large porphyroblasts of albite with inclusions of pargasitic hornblende are an important feature of this retrogressive stage (Treloar *et al.*, 2003).

From a tectonic viewpoint such features suggest that, in the NW Himalaya, eclogites generated in the subduction zone shortly after continental collision were exhumed along a cooling path by subsequent thrusting possibly associated with accretion of the metamorphic pile onto the base of the overriding plate (Treloar, 1995), and thus reached shallow crustal levels without any major high-temperature overprint. In contrast, in the Eastern Himalaya, rocks that were first brought into the eclogite field during formation of a deep continental root, were not exhumed fast enough to overcome the effects of thermal relaxation in the thickened continental crust and were subjected to strong granulite-facies overprinting at intermediate crustal levels (~ 30 km). Further decompression at high temperature exhumed the granulitized eclogites at shallow crustal levels (10–15 km), where these rocks were partly hydrated to amphibolites and finally cooled.

CONCLUSIONS

1 Granulitized eclogites found in the granitic orthogneiss of the Ama Drime Range (south Tibet) preserve microstructural and mineralogical evidence of four metamorphic stages (M1–M4) that define a clockwise exhumation path for the Lesser Himalayan Crystalline Sequence of the Eastern Himalaya. This exhumation path was characterized by decompression from

~2.0 GPa to ~0.4 GPa, followed by nearly isobaric cooling from ~775 °C to ~630 °C.

2 Compared with the P – T path recorded in the Greater Himalayan Sequence directly overlying the Ama Drime orthogneiss in the Kharta region, the P – T path of the Ama Drime granulitized eclogites begins at much higher metamorphic pressure and significantly higher temperature. Only during the late-stage cooling at low, amphibolite-facies, pressure conditions (M4), the P – T conditions of the Ama Drime eclogites (and country rocks) were the same as in the GHS.

3 This evidence confirms that in the investigated region, lying at the northern end of the Arun window, two lithotectonic units of different metamorphic evolution are exposed, with a lower eclogite-bearing unit and an upper medium- P granulite-facies unit.

4 A comparison between the metamorphic history of the different Himalayan eclogites suggests that in the NW Himalaya, eclogites were subjected to a decompressional evolution under decreasing temperatures, whereas in the Eastern Himalaya, eclogites were not exhumed fast enough to overcome the effects of thermal relaxation in the thickened continental crust and were subjected to strong granulite-facies overprinting at intermediate crustal levels.

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