Tectonic blocks in serpentinite mélange (eastern Cuba) reveal large-scale convective flow of the subduction channel

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ABSTRACT

Detailed petrological study of mid-oceanic ridge basalt–derived high-pressure amphibolite blocks from a fragment of the Caribbean subduction channel (La Corea serpentinite-matrix mélange, eastern Cuba) has revealed contrasted zoning patterns of garnet porphyroblasts, including well-defined complex oscillatory prograde-retrograde concentric zoning in one sample. Calculated pressure-temperature (*P-T*) conditions for this sample using mineral inclusion assemblages and isochemical *P-T* projections reveal large *P-T* recurrences best explained by large-scale convective movement of the tectonic block in a serpentinitic subduction channel. The *P-T* conditions attending garnet growth followed an overall counterclockwise path as a consequence of continued refrigeration of the subduction channel during ongoing underflow after its onset ca. 120 Ma. These findings constitute the first report of large-scale convective circulation of deeply subducted material in the subduction channel, and are consistent with the thermomechanical behavior of the channel predicted by numerical models.

INTRODUCTION

Subduction channels (or flow channels) are complex rock assemblies developed along the interface between the subducting and the hanging-wall plates in convergent margins. Shreve and Cloos (1986) and Cloos and Shreve (1988a, 1988b) first developed the concept to model the dynamics of convergent plate margins (prism accretion, sediment subduction, mélange formation, subduction erosion). They identified the subduction channel as a relatively shallow, thin layer of poorly consolidated sediment, dragged by the descending plate beneath the overriding plate and/or accretionary prism, where most of the subduction-driven deformation is concentrated and accretion of subducted material takes place. The concept can be applied to modern and ancient subduction complexes such as the Franciscan (e.g., Ernst, 1970), where the pressure-temperature (*P-T*) history of tectonic blocks in sediment-matrix melánges documents subduction of accreted materials down to 30 km depth. Cloos and Shreve (1988b) indicated that flow in the channel can be downward, upward (providing a mechanism of exhumation of accreted blocks), and convective.

Following the seminal work by Cloos and Shreve (1988a, 1988b), the subduction channel concept has been extended to much deeper near-subarc depths (e.g., Guillot et al., 2000, 2001, 2009; Gerya et al., 2002). At these depths, characterized by mantle rocks in the hanging wall, dehydration reactions in the subducting sediments, mafic crust, and ultramafic materials trigger the release of H_2O-rich fluids. Upward flow of these fluids triggers the transformation of upper plate peridotite into serpentinite (at temperatures below ~650 ºC; Ulmer and Trommsdorff, 1995), causing the formation of a ductile layer of serpentinite between the subducting and overriding plates, where much of the subduction-driven deformation concentrates. Thermomechanical models also predict downward, upward, and convective flow in this serpentinitic subduction channel (Gerya et al., 2002).

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Petrological studies have shown that high-pressure (HP) blocks accreted within the channels, i.e., metasedimentary and/or serpentinitic-matrix mélanges, undergo hairpin *P-T* paths (Ernst, 1988), indicating synsubduction exhumation in the channel. Synsubduction exhumation in the channel is also confirmed by blocks subducted and accreted during the early stages of subduction, because these blocks follow counterclockwise *P-T* paths documenting the progressive refrigeration of the nascent subduction system upon continued subduction of lithosphere (e.g., Wakabayashi, 1990). Although much petrological work has been presented to demonstrate up and down circulation, little work has been yet provided to demonstrate large-scale convective flow in subduction channels.

Garnet composition is very sensitive to changes in pressure and temperature, and cation diffusion in garnet is sufficiently slow to preserve zoning at low to moderate temperature (e.g., Konrad-Schmolke et al., 2005). Oscillatory zoning of Mn in HP garnet was described in Franciscan rocks by Dudley (1969). While Ghent (1988) indicated a potential kinetic control (reaction-diffusion problems) and disequilibrium growth, other possibilities for oscillatory zoning in Ca-Fe-Mn-Mg garnets include equilibrium processes during episodic inflections of *P-T* paths (e.g., Enami, 1998; Schumacher et al., 1999; García-Casco et al., 2002). Such inflections can only be related to complex material and/or heat flow in the lithosphere and, when identified in tectonic blocks of subduction mélanges, offer important clues for understanding the mechanics of subduction systems. In this paper we give the first petrological evidence that supports large-scale convective flow in serpentinitic channels.

GEOLOGICAL AND PETROLOGICAL SETTINGS

The Caribbean plate is fringed from Guatemala through the Greater Antilles to northern South America by subduction-related HP complexes, most of which formed after the onset of subduction (ca. 120 Ma) of the Protocaribbean (i.e., Atlantic) lithosphere below the Caribbean plate (Pindell et al., 2005; García-Casco et al., 2008a). Many of these HP complexes constitute serpentinite mélanges bearing exotic tectonic blocks of diverse nature (subducted oceanic lithosphere, forearc and/or arc and continental platform materials) and variable metamorphic grade (high-grade eclogite, garnet amphibolite and blueschist, and low-grade blueschist). In Cuba, serpentinitic mélanges are exposed along the >1000 km length of the island (Fig. 1A; Somin and Millán, 1981) and have been interpreted as fragments of Antillean subduction channel (García-Casco et al., 2006).

In eastern Cuba, the Sierra del Convento and La Corea serpentinite-matrix mélanges represent fragments of this subduction channel (Figs. 1B and 1C; see García-Casco et al., 2006, 2008b; Lázaro et al., 2009; Blanco-Quintero et al., 2010a, 2010b, for details of the following descriptions and for references on the geology of the region). These mélanges contain blocks of subducted high-grade garnet-amphibolite (Fig. 1D) and blueschist surrounded by sheared and massive antigoritite interpreted as the matrix of the subduction channel (Fig. 1E). Metamorphic conditions of garnet-amphibolite blocks (700–750 ºC; 15 kbar; ~50 km) indicate a very hot subduction zone environment that caused partial melting of subducted mid-oceanic ridge basalt (MORB) and the formation of tonalite-trondhjemite melts

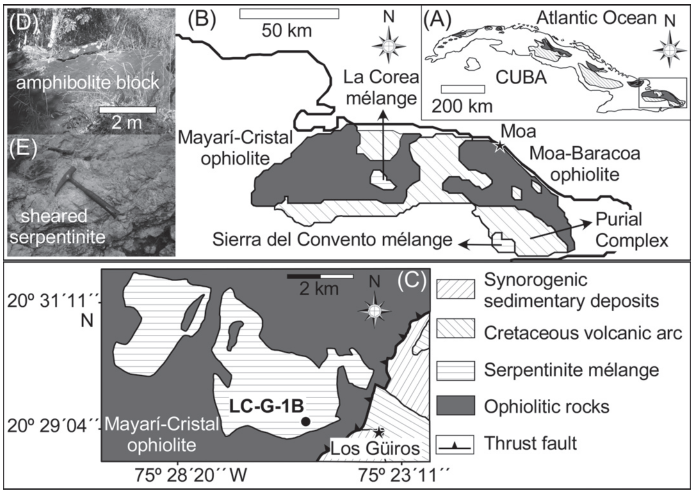

Figure 1. A–C are geological maps. A: Cuba. B: Eastern Cuba. C: La Corea mélange with indication of main geological complexes. Legend on right is for all maps. D: Photograph of outcrop showing amphibolite block. E: Photograph of outcrop showing serpentinite matrix in La Corea mélange; hammer length is 33 cm.

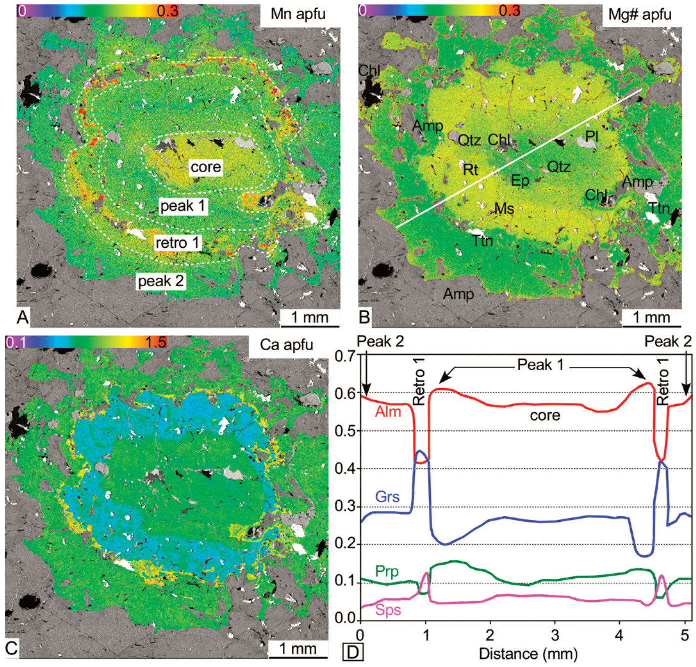

Figure 2. Quantitative X-ray images showing textures and garnet composition [color code, cations per 12 oxygens; see Appendix DR1 (see footnote 1) for details of calculations] of sample LC-G-1B. A: Mn. B: Mg#. Mineral abbreviations after Kretz (1983), except for the amphibole (Amp). C: Ca. D: Profile across garnet showing oscillations in composition. apfu—atom per formula unit.

crystallized at a similar depth. Most amphibolite blocks provide evidence for rather simple counterclockwise *P-T* paths characterized by high-*T* during accretion to the upper plate and low-*T* blueschist facies overprint during exhumation. Hot and ensuing cold conditions relate to onset of subduction of young oceanic Protocaribbean lithosphere ca. 120 Ma and to very slow synsubduction exhumation in the subduction channel (115–70 Ma), respectively. Final fast exhumation of the subduction channel occurred after an arc-platform–like terrane collision at 70–65 Ma.

A few blocks from these mélanges, however, show evidence for more complex *P-T* evolutions in the channel. In this paper we give detailed information for a singular block of epidote-garnet amphibolite from the La Corea mélange (Fig. 1C; sample LC-G-1B) that provided a complex *P-T* evolution.

PETROGRAPHY

The mineral assemblage of amphibolite sample LC-G-1B consists of calcic (pargasitic) amphibole-epidote-garnet-titanite-rutile-quartz-phengite, and apatite. Amphibole is medium to coarse grained, with grains as long as 4 mm, oriented parallel to the foliation. Garnet porphyroblasts are as much as 6 mm in diameter (Fig. 2) and are anhedral. The porphyroblasts contain inclusions of rutile, titanite, apatite, epidote, plagioclase, quartz, calcic amphibole, phengite, and chlorite, and their xenoblastic rims penetrate into the amphibolitic matrix and/or appear replaced by retrograde amphibole ± chlorite (Fig. 2B). Epidote is abundant and occurs as euhedral patchy zoned crystals 0.1–0.5 mm long. Phengite is scarce and appears as medium-size flakes.

Retrograde overprints are composed of combinations of actinolite, glaucophane, albite, clinozoisite, chlorite, and phengite. These retrograde minerals are fine grained and form reaction rims around peak metamorphic minerals and locally fill fractures. Retrograde albite is scarce and appears aggregated with epidote, titanite, and phengite. Chlorite replaces garnet and pargasitic amphibole. Glaucophane appears as small patches replacing pargasitic amphibole and indicates a high-pressure–low-temperature trajectory during exhumation.

MINERAL COMPOSITION

The analytical methods and chemical composition of rocks and minerals are presented in Appendices DR1 and DR2 (see the GSA Data Repository[1]), respectively. Amphibole is calcic, with $(Na^{+}K)_A$ = 0.51–0.61 apfu (atom per formula unit) for peak edenite-pargasite and 0.04–0.48 apfu for retrograde actinolite-magnesiohornblende compositions. The peak compositions are rich in Na_A (maximum, max. 0.52 apfu), total Al (max. 3.16 apfu), and Mg# (max. 0.64), and poor in Si (minimum, min. 6.07 apfu). Retrograde compositions have higher Si (max. 7.90 apfu) and Mg# (max. 0.79) and lower Na_A (min. 0.02 apfu) and total Al (min. 0.35 apfu) contents. Retrograde glaucophane is near pure end-member glaucophane with Si = 7.97, Al = 1.58, Na_B = 1.87, Na_A = 0.07, and Ca = 0.07 apfu, and intermediate Mg# (0.57).

Garnet is relatively rich in almandine (Xalm max. 0.64) and, to some extent, grossular (0.20–0.30), and is poor in pyrope and spessartine (0.15–0.20 and 0.02–0.10, respectively). It is concentrically zoned. In the case illustrated in the quantitative images of Figures 2A–2C and in the profile of Figure 2D, four zones can be identified: (1) a low-*T* core having low Mg# and high Mn, with inclusions of chlorite, albite, epidote, and quartz, overgrown by (2) a prograde high Mg# zone (peak 1), with inclusion of rutile, quartz, pargasite, and phengite, (3) a retrogressive xenomorphic zone likely generated after garnet dissolution characterized by high Mn and low Mg# (retro 1) associated with inclusions of chlorite, titanite, and actinolitic amphibole confirming its retrogressive nature, and (4) an outer rim of prograde high Mg# zone (peak 2). Large compositional variations characterize the internal retrogressive event retro 1 (Fig. 2D).

Epidote grains have pistacite (Fe^{3+}/([Al-2] + Fe^{3+}) contents of 0.10–0.30. Phengitic mica exhibits a range in celadonite contents (Si =

[1]GSA Data Repository item 2011039, Appendix DR1 (analytical techniques, image processing methods, and solution models used in the thermodynamic calculations) and Appendix DR2 (whole rock and mineral composition table), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

6.23–6.97 apfu), with Mg# = 0.62–0.71; the cores of the matrix flakes have lower celadonite and higher Na contents (max. 0.35 apfu), indicating higher temperature of formation. Plagioclase is almost pure albite in composition ($X_{ab} > 0.99$). Chlorite (inclusions and late retrograde replacements in the matrix) displays a large compositional variation denoting variable *P-T* of formation and diffusion problems during retrogression.

PRESSURE-TEMPERATURE CALCULATIONS

The *P-T* conditions were calculated using the average *P-T* method (Powell and Holland, 1994) and software THERMOCALC (Holland and Powell, 1998; version 3.31 and data set 5.5). The activities and activity uncertainties of end members were obtained with software AX. The prepeak *P-T* conditions were determined for the assemblage Grt + Ep + Ab + Chl + Qtz + H_2O (Kretz, 1983) using the composition of garnet cores and associated inclusions. The conditions for peak 1 garnet were calculated using the compositions of associated inclusions of Amp and Ms (+H_2O). The conditions for peak 2 garnet were calculated with the same assemblage using the composition of matrix pargasite and the cores of matrix muscovite. Retrograde conditions were calculated using actinolitic Amp + Grt + Chl + Qtz + H_2O (retro 1) and actinolitic Amp + Chl + Ep + Ms + Qtz + Ab + H_2O (retro 2), using the composition of included and matrix phases, respectively.

The calculated physical conditions indicate a complex *P-T* path characterized by first an increase in *P-T* from the garnet core (536 ± 22 ºC, 10.6 ± 1.6 kbar) to the internal peak 1 zone (634 ± 71 ºC, 15.9 ± 2.0 kbar), a strong decrease in *P-T* for the internal retro 1 zone (446 ± 19 ºC, 11.4 ± 2.0 kbar), a second increase for the peak 2 stage (590 ± 54 ºC, 16.4 ± 2.1 kbar), and a decrease for the final retro 2 stage (471 ± 62 ºC, 11.1 ± 1.6 kbar). Note that the highest *P-T* condition corresponds to the internal peak 1 zone rather than the external final overgrowth (peak 2).

An isochemical *P-T* phase diagram (pseudosection) was calculated for sample LC-G-1B using THERMOCALC (same version as above). The physical conditions predicted for the different zones of garnet using mineral isopleths and mineral assemblages (Fig. 3A) are in agreement with *P-T* conditions calculated by the average *P-T* method. The distribution of isopleths of chemical composition and abundance of garnet (Fig. 3B) indicate that garnet was consumed during formation of retro 1 zone. This conclusion reveals that fluid infiltration occurred during the retrograde steps of the *P-T* path.

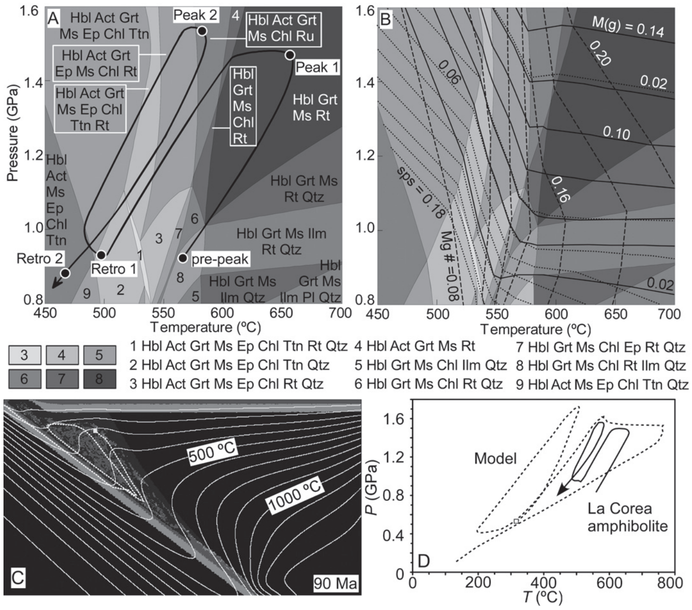

Figure 3. A: Isochemical pressure-temperature (*P-T*) equilibrium phase diagram for studied sample in the KNCFMMnASTHO system (SiO_2 = 47.06, Al_2O_3 = 8.32, TiO_2 = 1.85, Fe_2O_3 = 1.54, FeO = 11.32, MgO = 16.39, MnO = 0.23, CaO = 11.19, Na_2O = 1.88, K_2O = 0.23, percent molar units; excess H_2O is assumed). Mineral abbreviations after Kretz (1983). Color code indicates thermodynamic variance. *P-T* trajectory calculated using mineral assemblages, garnet composition isopleths, and average *P-T* data are indicated. B: Isopleths of Mg# (dashed lines), spessartine (dotted lines), and modal abundance of garnet (solid lines). C: Thermomechanical model for subduction of young (20 Ma) lithosphere with geometry and thermal structure of subduction zone after 900 km of convergence at subduction rate of 3 cm/yr (i.e., 30 m.y. after onset of subduction). Sketch represents 110 × 100 km areas. For details of numerical model, see Gerya et al. (2002, their table 1 and model G). White marker shows trajectory of representative accreted oceanic crust fragment subjected to large-scale circulation in channel. D: *P-T* path calculated for representative oceanic crust fragment shown in C versus paths of amphibolite from La Corea mélange.

DISCUSSION

Major element abundances of the studied sample indicate a protolith of MORB composition similar to other metabasite blocks from the La Corea mélange (Blanco-Quintero et al., 2010a). The *P-T* path followed by the amphibolite block was counterclockwise for the initial stages of prograde-retrograde metamorphism (core > peak 1 > retro 1) and is consistent with the paths of other amphibolite blocks of eastern Cuba mélanges as described by García-Casco et al. (2008b), Lázaro et al. (2009), and Blanco-Quintero et al. (2010a). These authors indicated that the thermal history of these blocks documents onset of subduction of young oceanic lithosphere followed by exhumation in the subduction channel. Colder conditions during exhumation relates to cooling of the subduction system as subduction proceeded, involving development of the serpentinite subduction channel after hydration of the upper plate peridotite at <650 ºC by fluids released from the downgoing slab. Similar counterclockwise *P-T-t* (*t* is time) evolutions are predicted by thermomechanical models of nascent subduction systems followed by continued subduction and development of subduction channels (Gerya et al., 2002).

The second part of the *P-T* path (retro 1 > peak 2 > retro 2) is critical for understanding the geodynamic scenario. A key aspect is that the prograde growth of garnet (peak 2) indicates substantial reburial (ΔP = 6 kbar; Δdepth = 20 km) to depths similar to those that characterize peak 1 stage (i.e., accretion stage). Such a reburial excursion undergone by the studied block is possible due to (1) collision, (2) subduction erosion, or (3) large-scale convective circulation of the subduction channel. The recurrent prograde-retrograde evolution described here contrasts with the simple prograde-retrograde *P-T* evolution of most blocks from eastern Cuba mélanges. This contrast invalidates collision and subduction erosion, because these scenarios would have produced similar complex *P-T* paths in most, if not all, blocks of the mélanges. Contrasted *P-T* histories, however, are expected for individual blocks flowing in a viscous dynamic medium of the channel (Cloos and Shreve, 1988a; Schwartz et al., 2001; Gerya et al., 2002; Gorczyk et al., 2007).

A second important aspect is that the temperature of peak 2 stage was lower than that of peak 1 stage, consistent with cooling of the subduction system with time. This process would permit the development of serpentinite after hydration of the upper plate mantle, expanding the channel in width and depth. Such expansion of ductile material makes feasible the convective flow of the channel, and hence the reburial of circulating blocks to depths greater than those attained at the earlier accretion stage. Note that a total 100–150 °C cooling of the subduction channel suggested by the geometry of the *P-T* path (Fig. 3A) is at the lower limit of results of numerical experiments (Gerya et al., 2002) predicting 125–300 °C cooling of channel rocks in a few tens of millions of years after the onset of subduction (Fig. 3D).

Complex fluxes of material in the channel, including large-scale convective flow, are predicted by thermomechanical models of subduction zones (Gerya et al., 2002; Gorczyk et al., 2007). However, the expected petrological consequences of convective flow of blocks from subduction mélanges have not been previously documented. Oscillatory zoning of garnet reflecting possible prograde-retrograde fluctuations in the subduction environment was described by Dudley (1969) for the Franciscan Complex, by García-Casco et al. (2002, 2006) for serpentinite mélanges from central and western Cuba, and by Tsujimori et al. (2006) for serpentinite mélanges from Guatemala. Only García-Casco et al. (2002) interpreted these features, suggesting subtle *P-T* fluctuations related to tectonic forcing during subduction of oceanic material rather than to processes in the subduction channel. However, these and other similar examples, if properly identified as the result of complex flow in the channel, will provide further evidence for this important aspect of the dynamics of subduction systems.

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