2- TECTONIC BLOCKS IN SERPENTINITE MÉLANGE
(EASTERN CUBA) REVEAL LARGE-SCALE CONVECTIVE FLOW OF THE SUBDUCTION CHANNEL

I.F. Blanco-Quintero\(^1\), A. García-Casco\(^{1,2}\), T. V. Gerya\(^{3,4}\)

\(^1\) Departamento de Mineralogía y Petrología, Universidad de Granada, Fuentenueva s/n, 18002-Granada, Spain
\(^2\) Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Fuentenueva s/n, 18002-Granada, Spain
\(^3\) Department of Geosciences, Swiss Federal Institute of Technology, 8093 Zurich, Switzerland
\(^4\) Department of Geology, Moscow State University, 119899 Moscow, Russia

ABSTRACT
Detailed petrological study of MORB-derived high pressure amphibolite blocks from a fragment of the Caribbean subduction channel (La Corea serpentinite-matrix mélange, E Cuba) has revealed contrasted zoning patterns of garnet porphyroblasts, including well defined complex oscillatory prograde-retrograde concentric zoning in one sample. Calculated 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. P-T conditions attending garnet growth followed an overall counter-clockwise path as a consequence of continued refrigeration of the subduction channel during ongoing underflow after its onset at 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 thermo-mechanical behavior of the channel predicted by numerical models.

Keywords: subduction channel; garnet; convective circulation; numerical modeling
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, b) first developed the concept to model the dynamics of convergent plate margins (prism accretion, sediment subduction, mélange formation, subduction erosion…). These authors identified the subduction channel as a relatively shallow, thin layer of poorly consolidated sediment, dragged by the descending plate beneath the overriding plate/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 P-T history of tectonic blocks in sediment-matrix mélanges document 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 these authors, the subduction channel concept has been extended to much deeper near-sub-arc 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$_2$O-rich fluids. Upward flow of these fluids triggers the transformation of upper plate peridotite into serpentinite (at temperature below ca. 650 °C; Ulmer and Trommsdorff, 1995), causing the formation of a ductile layer of serpentinite in 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).

Petrological studies have shown that HP blocks accreted within the channels —i.e., metasedimentary/serpentinitic-matrix mélanges— undergo hairpin P-T paths (Ernst, 1988), indicating syn-subduction exhumation in the channel. Syn-subduction exhumation in the channel is also confirmed by blocks subducted/accreted during the early stages of subduction, for these blocks follow counter-clockwise 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 provide to demonstrated 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/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 petrological evidence for the first time 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 high pressure (HP) complexes, most of which formed after the onset of subduction (at 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, fore-arc/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 all 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 (Fig. 1B, C; see García-Casco et al., 2006, 2008b; Lázaro et al., 2009; Blanco-Quintero et al., 2010a and b, 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 antigorite interpreted as the matrix of the subduction channel (Fig. 1E). Metamorphic conditions of garnet-amphibolite blocks (700–750 ºC; 15 kbar; ca. 50 km) indicate a very hot subduction zone environment that caused partial melting of subducted MORB and the formation of tonalite-trondhjemite melts crystallized at a similar depth. Most amphibolite blocks provide evidence for rather simple counter-clockwise 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 at ca. 120 Ma and to very slow syn-subduction 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 evidences 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) which has provided a rather complex P-T evolution.

**ANALYTICAL TECHNIQUES AND METHODS**

Whole-rock major element compositions were determined with a PHILIPS Magix Pro (PW-2440) X-ray fluorescence equipment (University of Granada) using a glass beads, made of 0.6g of powdered sample diluted in 6g of Li$_2$B$_4$O$_7$.

Mineral compositions were obtained using WDS with a CAMECA SX-100 microprobe (University of Granada) operated at 15 kV and 15 nA. Amphibole composition was normalized following the procedure of Leake et al. (1997), and Fe$^{3+}$ was estimated after the method of Schumacher (in Leake et al., 1997). Garnet composition was normalized to 12 oxygens and 8 cations, with Fe$^{3+}$ estimated by stoichiometry. Epidote and plagioclase were normalized to 12.5 and 8 oxygens,
respectively, and $\text{Fe}_{\text{total}} = \text{Fe}^{3+}$. White mica and chlorite were normalized to 22 and 28 oxygens, respectively, and $\text{Fe}_{\text{total}} = \text{Fe}^{2+}$.

Elemental X-ray images were obtained with the same machine operated at 20 kV, 150 nA beam current, step (pixel) size of 7 µm and counting time of 30 ms. The images were processed with Imager software (Torres-Roldán and García-Casco, unpublished) to obtain quantitative images of garnet composition (expressed in atoms per 12 oxygen formula unit). The procedure of Bence and Albee (1968) was followed for matrix correction by using the composition of an internal garnet standard analyzed with the electron microprobe. In the images the other minerals are masked out, and the resulting images are overlain onto a gray-scale “Z” image calculated by the sum of the products of the counts by atomic number (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, Ba, K, P, F and Cl). The profile was extracted from the quantified X-ray images of Si, Al, Fe, Mn, Mg, and Ca with a resolution of 7 µm/point (total number of points plotted: 518) and transformed to continuous lines by regression. The atomic concentration of elements per formula units is abbreviated apfu, the Mg number of minerals (Mg#) is expressed as $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$.

Solution models used in the thermodynamic calculations for amphibole, chlorite, epidote, plagioclase and muscovite are from Diener et al. (2007), Holland et al. (1998), Holland and Powell (1998), Holland and Powell (2003) and Coggon and Holland (2002) respectively, and for garnet and ilmenite from White et al. (2005).

Figure 1. A: Geological maps of A: Cuba, B: eastern Cuba, and C: La Corea mélange with indication of main geological complexes. Photographs of outcrops showing D: amphibolite block and E: serpentinite matrix in La Corea mélange. Legend is for all maps.
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 up to 4 mm in length, oriented parallel to the foliation. Garnet porphyroblasts are up to 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 of 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

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 NaA (max. 0.52 apfu), total Al (max. 3.16 apfu) and Mg# (max. 0.64), and poor in Si (min. 6.07 apfu). Retrograde compositions have higher Si (max. 7.90 apfu) and Mg# (max. 0.79) and lower NaA (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, NaB = 1.87, NaA = 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 Figure 2A-C 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 (Fe3+/([Al-2]+Fe3+) contents of 0.10–0.30. Phengitic mica exhibits a range in celadonite contents (Si = 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
Table 1. Whole rock and mineral compositions.

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<th>K$_2$O</th>
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<td>Retro-1</td>
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51
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.

**P-T CALCULATIONS**

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 (Holland and Powell, unpublished). The pre-peak P-T conditions were determined for the assemblage Grt+Ep+Ab+Chl+Qtz+H2O 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 (+H2O). The conditions for peak-2 garnet were calculated with the same assemblage using the composition of matrix paragasite and the cores of matrix
muscovite. Retrograde conditions were calculated using actinolitic Amp+Grt+Qtz+H2O (retro-1) and actinolitic Amp+Chl+Ep+Ms+Qtz+Ab+H2O (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 ± 54ºC, 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 correspond 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) indicates 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.

**DISCUSSION**

Major element abundances of the studied sample indicate a protolith of MORB composition similar to other metabasite blocks from the La Corea mélangé (Blanco-Quintero et al., 2010a). The P-T path followed by the amphibolite block was counter-clockwise 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 (García-Casco et al., 2008b; Lázaro et al., 2009; Blanco-Quintero et al., 2010a). These authors indicated that the thermal history of these blocks document 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 counter-clockwise P-T-t evolutions are predicted by thermal-mechanical 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 experienced by the studied block is possible due to a) collision, b) subduction erosion, or c) large-scale convective circulation of the subduction channel. The recurrent prograde-retrograde evolution described above contrasts with the simple prograde-retrograde P-T evolution of most blocks from eastern Cuba mélanges. This contrast invalidates collision and subduction erosion, for these scenarios would have produced similar complex P-T paths in most, if not all, blocks.
Figure 3. A: Isochemical P-T equilibrium phase diagram for the studied sample in the KNCFMMnASTHO system (SiO$_2$ = 47.06, Al$_2$O$_3$ = 8.32, TiO$_2$ = 1.85, Fe$_2$O$_3$ = 1.54, FeO = 11.32, MgO = 16.39, MnO = 0.23, CaO = 11.19, Na$_2$O = 1.88, K$_2$O = 0.23, percent molar units; excess H$_2$O is assumed). Mineral abbreviations are hb (hornblende), act (actinolite), g (garnet), ep (epidote), mu (muscovite), chl (chlorite), ru (rutile), ttn (titanite), ilm (ilmenite), pl (plagioclase), q (quartz). Color code indicates thermodynamic variance. The P-T trajectory calculated using mineral assemblages, garnet composition isopleths, and average P-T data is indicated. B: Isopleths of Mg# (dashed lines), spessartine (dotted lines) and modal abundance of garnet (solid lines). C: Thermo-mechanical model for subduction of young (20 m.y.) lithosphere with the geometry and the thermal structure of the subduction zone after 900 km of convergence at a subduction rate of 3 cm/y (i.e., 30 m.y. after onset of subduction). The sketch represents 110 X 100 km areas. For details of numerical model see table 1, model G; in Gerya et al. (2002). White marker shows the trajectory of a representative accreted oceanic crust fragment subjected to large-scale circulation in the channel. D: P-T path calculated for the representative oceanic crust fragment shown in C vs paths of amphibolite from La Corea mélange.

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; Gorzyck 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
re-burial 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 Myrs after the onset of subduction (Fig. 3D).

Complex fluxes of material in the channel, including large-scale convective flow, are predicted by thermo-mechanical models of subduction zones (Gerya et al., 2002; Gorzyck 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, García-Casco et al. (2002, 2006) for serpentinite mélanges from central and western Cuba, and 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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