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Blueschist preservation in a retrograded, high-pressure, low-temperature metamorphic terrane, Tinos, Greece: Implications for fluid flow paths in subduction zones

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[1] The preservation of high-pressure, low-temperature (HP-LT) mineral assemblages adjacent to marble unit contacts on the Cycladic island of Tinos in Greece was investigated using a new type of digital outcrop mapping and numerical modeling of metamorphic fluid infiltration. Mineral assemblage distributions in a large blueschist outcrop, adjacent to the basal contact of a 150-meter thick marble horizon, were mapped at centimeter-scale resolution onto digital photographs using a belt-worn computer and graphics editing software. Digital mapping reveals that while most HP-LT rocks in the outcrop were pervasively retrograded to greenschist facies, the marble-blueschist contact zone underwent an even more intense retrogression. Preservation of HP-LT mineral assemblages was mainly restricted to a 10–15 meter zone (or enclave) adjacent to the intensely retrograded lithologic contact. The degree and distribution of the retrograde overprint suggests that pervasively infiltrating fluids were channelized into the marble-blueschist contact and associated veins and flowed around the preserved HP-LT enclave. Numerical modeling of Darcian flow, based on the field observations, suggests that near the marble horizon, deflections in fluid flow paths caused by flow channelization along the high-permeability marble-blueschist contact zone likely resulted in very large fluid fluxes along the lithologic contact and significantly smaller fluxes (as much as 8 times smaller than the input flux) within the narrow, low-flux regions where HP-LT minerals were preserved adjacent to the contact. Our results indicate that lithologic contacts are important conduits for metamorphic fluid flow in subduction zones. Channelization of retrograde fluids into these discrete flow conduits played a critical role in the preservation of HP-LT assemblages.

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Theme: Trench to Subarc: Diagenetic and Metamorphic Mass Flux in Subduction Zones
Guest Editors: Gray Bebout, Jonathan Martin, and Tim Elliott

1. Introduction

[2] Regional metamorphic fluid flow has been well documented in accretionary terranes as well as in the deepest levels of subduction zones where arc magmas are generated [e.g., *Noll et al.*, 1996; *Ague*, 1997; *Manning*, 1997; *Breeding and Ague*, 2002]. However, for intermediate depths of subduction involving high-pressure, low temperature (HP-LT) rocks, fluid fluxes and flow paths associated with both prograde and retrograde metamorphic fluid flow remain controversial. Thermal models and devolatilization reactions suggest that fluids are produced by slab dehydration and HP-LT prograde metamorphism along the entire depth range of subduction [*Peacock*, 1990]; thus it seems likely that significant quantities of fluid must have moved through HP-LT metamorphic terranes at some time during subduction and/or exhumation. Most studies of HP-LT crustal rocks from the Alps and the Cycladic Archipelago of Greece indicate little evidence for regional-scale prograde fluid flow [e.g., *Philippot and Selverstone*, 1991; *Selverstone et al.*, 1992; *Getty and Selverstone*, 1994; *Barnicoat and Cartwright*, 1995; *Ganor et al.*, 1996; *Putlitz et al.*, 2000]. However, exhumation of HP-LT rocks in the Cyclades was commonly accompanied by a near-pervasive retrogression of HP-LT assemblages that required the presence of fluids [e.g., *Bröcker and Franz*, 1998]. The fact that HP-LT mineral assemblages are preserved at all suggests that retrograde fluid flow was highly channelized. Possible conduits for regional, retrograde fluid flow in subduction zones include km-scale tectonic structures (such as mélange zones); extensive, interconnected vein networks; or lithologic contacts, where mechanical weaknesses between differing lithologies may cause enhanced permeability and facilitate fluid flow [e.g., *Rye et al.*, 1976; *Bebout and Barton*, 1989; *Baumgartner and Ferry*, 1991; *Ferry*, 1994; *Ague*, 1997; *Ferry et al.*, 2001]. We have developed a new, field-based, real-time digital outcrop mapping technique to look for retrograde fluid flow signatures by examining the roles of fluid flux and channelized flow paths in the preservation of HP-LT mineral assemblages during exhumation and retrogression of a HP-LT terrane on the island of Tinos, Cycladic Archipelago, Greece. We have tested our interpretations using a numerical fluid-flow model that incorporates digital field-mapping observations.

2. Geologic Setting

[3] Many of the Cycladic islands of Greece are dominated by rocks of the Attic-Cycladic Blueschist Belt, a regionally extensive band of deeply subducted crustal rocks that underwent HP-LT metamorphism to blueschist and eclogite facies during Cretaceous to Eocene subduction of the Apulian microplate beneath Eurasia [*Schliestedt and Matthews*, 1987; *Okrusch and Bröcker*, 1990; *Bröcker and Enders*, 1999]. Metamorphic conditions reached 15 ± 3 kbar and 450–550°C [e.g., *Bröcker et al.*, 1993]. Subsequent Oligocene-Miocene isothermal exhumation resulted in tectonic juxtaposition of HP-LT crust and assorted overlying rock types, consisting of amphibolites, greenschists, and unmetamorphosed rocks. Exhumation was accompanied by retrograde fluid infiltration, which was nearly pervasive in some regions and caused widespread greenschist facies overprinting of HP-LT rocks. Greenschist facies conditions reached 4–7 kbar and 450–500°C [*Schliestedt*

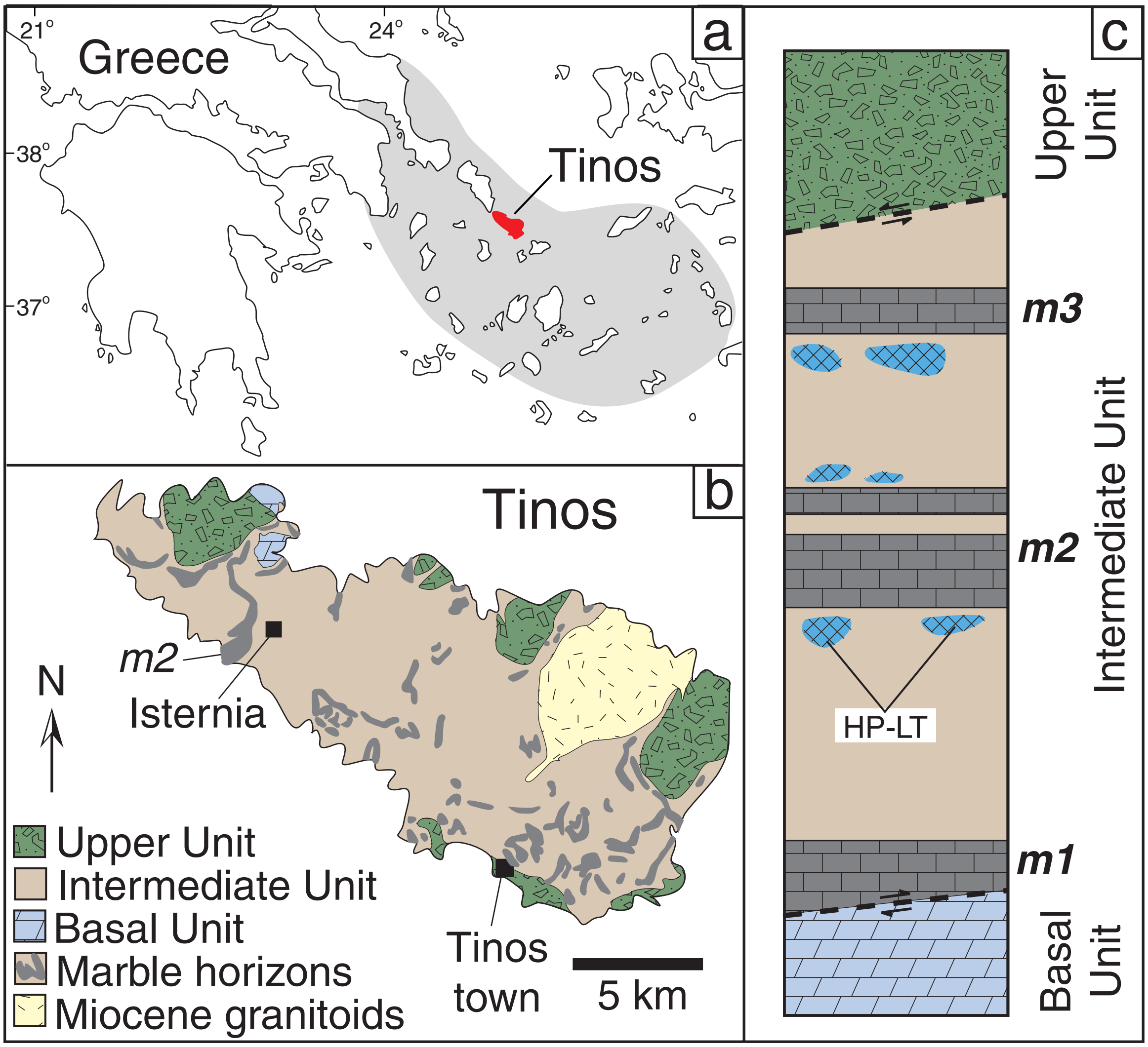

Figure 1. (a) Map of Greece and Cyclades (modified from *Bröcker et al.* [1993]). Cycladic island of Tinos marked in red. Extent of Attic-Cycladic blueschist belt shown in gray. (b) Geologic map of Tinos [after *Melidonis*, 1980; *Bröcker et al.*, 1993]. Exposed rocks consist mostly of HP-LT Intermediate Tectonic Unit (ITU). ITU marble horizons in dark gray. Contact zone from marble horizon *m*2 near Isternia shown in detail in Figure 2a. (c) Schematic tectono-stratigraphic section for Tinos [after *Bröcker and Franz*, 1998]. Three tectonic units separated by major faults (dashed black lines). ITU is major HP-LT unit, but mostly retrograded to greenschist facies. ITU contains three major marble horizons (*m*1, *m*2, *m*3). HP-LT remnant assemblages (blue, cross-hatched fields) well preserved only adjacent to marble horizon contacts.

and Matthews, 1987; *Okrusch and Bröcker*, 1990]. The source for the infiltrating retrograde fluids is not known, but was likely related to (1) dehydration of subducting oceanic crust, (2) tectonic underthrusting and prograde metamorphic devolatilization of newly subducting rock packages [*Wijbrans et al.*, 1993], and/or (3) fluid release from crystallizing magmas. Despite the apparent pervasive nature of the retrograde fluid infiltration on islands like Tinos, isolated HP-LT assemblages were preserved, often in close proximity to their retrograded equivalents. Rocks exposed on Tinos have been divided into three tectonic units (Figure 1b and 1c) [cf. *Melidonis*, 1980; *Bröcker and Franz*, 1998]. The Upper Tectonic Unit (UTU) is of limited exposure and consists of a ~250 m sequence of serpentinites, metagabbros, ophicalcites, phyllites, and amphibolites that are interpreted to be a dismembered ophiolite complex [*Katzir et al.*, 1996; *Putlitz et al.*, 2001]. UTU rocks underwent greenschist facies metamorphism during tectonic emplacement and fluid infiltration, but did not achieve HP-LT conditions. The base of the UTU is marked by a low-angle normal fault [*Avigad and Garfunkel*, 1989]. The Intermediate Tectonic Unit (ITU) makes up most of Tinos and consists of a 1250–1800 m sequence of marbles, calcareous schists, metasediments, metacherts, metatuffs, and metabasalts that underwent both HP-LT metamorphism and the widespread greenschist facies overprint. Due to the nearly pervasive retrogression of the ITU on Tinos, HP-LT assemblages are preserved only in a few isolated zones. The Basal Tectonic Unit (BTU) occurs only in the northwestern corner of Tinos and consists of intercalated greenschist facies dolomitic limestones and phyllites that were overthrust by the other tectonic units [*Avigad and Garfunkel*, 1989]. Because the dolomitic marble-dominated unit lacks diagnostic mineral assemblages, the metamorphic history of the BTU has been difficult to decipher [*Bröcker and Franz*, 1998]. Preliminary work indicating high-silica phengite compositions suggests that the BTU underwent HP-LT metamorphism (M. Bröcker and L. Franz, manuscript in preparation, 2002).

[4] The ITU contains three thick marble sequences that are used as marker horizons. The marbles are described from the bottom of the sequence up as *m*1, *m*2, and *m*3 [*Melidonis*, 1980]. The original stratigraphic sequence of interlayered marbles and metasediments appears to be structurally intact [*Bröcker and Franz*, 1998]. Most major zones of HP-LT preservation on Tinos occur adjacent to the contacts of thick marble horizons (Figure 1c). Similarly preserved HP-LT rocks are commonly associated with marble units in the Cyclades, but the reason for the spatial association remains unresolved. One explanation for the preservation of HP-LT rocks adjacent to the upper contact of the Main Marble complex on Sifnos was the capping effect of impermeable marble units that prevented the upward, cross-layer infiltration of retrograde fluids from overprinting the blueschists [*Matthews and Schliestedt*, 1984]. This mechanism, however, is not applicable for Tinos, as retrograde fluid infiltration was mostly layer-parallel [*Bröcker*, 1990; *Bröcker and Franz*, 1998]. We investigated one of the best-preserved HP-LT exposures at the base of the *m*2 marble horizon near the village of Isternia on Tinos for digital outcrop mapping analysis and numerical modeling of the effects of metamorphic fluid flow on blueschist preservation (Figure 1b).

3. Digital Outcrop Mapping

[5] A new, real-time, digital outcrop mapping technique was developed to examine mineral assemblage distributions in outcrops relative to lithologic, structural, and metasomatic features while in the field. Using a digital camera, high-resolution photographs of an outcrop were taken and downloaded into a portable, belt-mounted computer. The outcrop location was geo-referenced using handheld GPS and annotated into the image file. The images were loaded into graphics editing software and juxtaposed to create a digital backgound for the outcrop map (Figure 2a). Geologic features (i.e., lithologic units, contacts, faults, veins, etc.) were digitized onto the basemap at cm-scale resolution and labeled while standing at the outcrop. Direct examination of the outcrop and numerous hand samples at the outcrop allowed precise mapping of the spatial distribution of metamorphic mineral assemblages onto the digital basemap. Diagnostic minerals are coarse-grained in hand sample, facilitating easy field identification of mineral assemblage zones (Figure 2b) on the basis of relative abundance of chlorite (greenschist facies) and glaucophane (blueschist facies) as follows: (1) Zone 1 = chlorite abundant, glaucophane not visible; (2) Zone 2 = modal% chlorite > modal% glaucophane; (3) Zone 3 = modal% glaucophane > modal% chlorite; and (4) Zone 4 = glaucophane abundant, chlorite not visible. Thin sections for selected samples were prepared and examined in the laboratory to confirm the field observations (Figure 2b).

4. Mineral Assemblage Distributions

[6] Digital outcrop mapping of the relatively well-preserved HP-LT blueschist exposure near Isternia reveals distinct distributions of HP-LT and retrograde mineral assemblages. The 250-meter-long

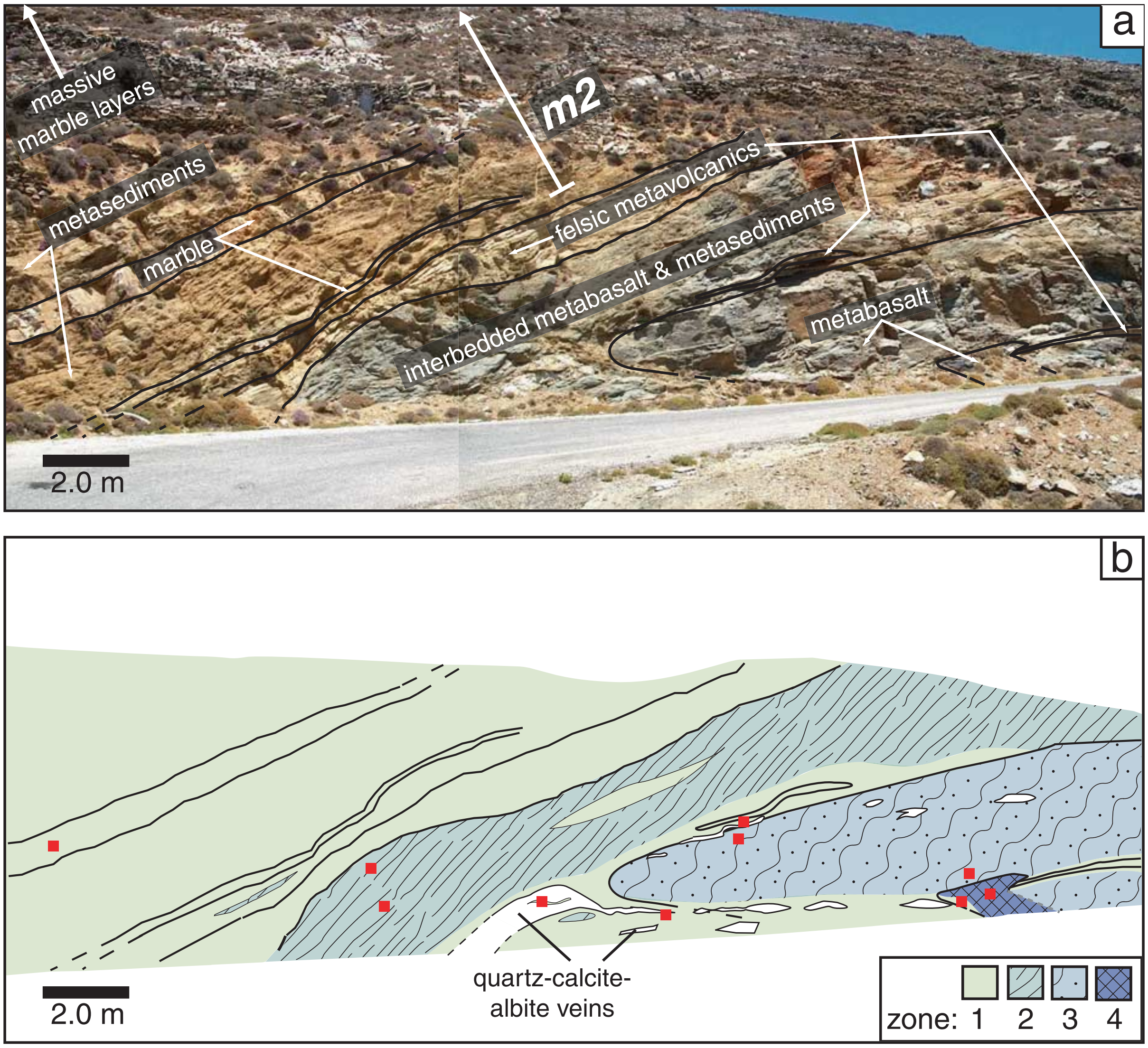

Figure 2. (a) Digital photographs of outcrop at base of *m*2 marble horizon near Isternia. Lithologic contacts drawn in black. Outcrop preserves structurally coherent section of ITU with no evidence for faulting. Massive marbles of *m*2 (not seen in photos) occur ~5 meters beyond top-left corner of photo. Base of *m*2 marked by lowermost marble layer. (b) Digitized mineral assemblage distribution overlay at same scale as Figure 2a. Lithologic contacts from Figure 2a included for reference. Basal contact zone of *m*2 marble unit consists of strongly retrograded (greenschist facies; Zone 1) thin calcite marbles, acidic metavolcanics, and interlayered metasediments. Below *m*2, massive metabasalt, interlayered metasediments and thin metabasalts, and felsic metavolcanics variably retrograded. Extent of retrogression increases outward (Zones 2–3) from a small region of relatively unretrograded blueschist facies rocks preserved ~7 m from basal *m*2 contact (Zone 4). Zone 1 greenschist assemblages reappear ~4 m below lower-right corner of photo in Figure 2a. Quartz-calcite-albite veins up to 0.5 m wide with greenschist facies, retrograded selvages (Zone 1) occur adjacent to contact zone. Red squares indicate samples used for petrographic verification of mineral assemblages.

roadcut outcrop contains an intact section of the ITU immediately below the *m*2 marble horizon (Figures 2a and 2b). No evidence for faulting was observed. The base of the *m*2 horizon is not a sharp marble-schist contact, but instead is a gradational, 10–15 m wide contact zone consisting of interlayered calcite marbles, metasediments, and felsic metavolcanic rocks (Figure 2a). The layered contact zone quickly grades into massive calcite marbles upsection (not shown in Figure 2a). Quartz-calcite-albite veins up to 0.5 m thick are present in some parts of the outcrop. Thin marble layers, as well as all rock types within the *m*2 contact zone contain greenschist facies mineral assemblages that reflect near complete retrogression. Altered zones adjacent to the large veins also contain a greenschist facies assemblage. Below the *m*2 contact, remnant HP-LT mineral assemblages in metabasalts and metasediments are variably preserved in a distinct zonation pattern.

[7] On the basis of field observations and petrographic examination of thin sections in the laboratory, four mineral zones were mapped for the outcrop with increasing distance from the base of the *m*2 marble horizon (Figure 2b). Sparse, remnant grains of glaucophane, often visible only in thin section, occur in all zones and indicate HP-LT protoliths for the greenschist overprint. Zone 1 is found throughout the basal part of *m*2, along the contact, and adjacent to large veins and is dominated by a greenschist facies mineral assemblage consisting of chlorite, calcite, actinolite, quartz, epidote, albite, phengite, ± titanite, ± pyrite, ± magnetite, ± glaucophane relics (Figure 2b). Intense albitization and carbonation, in addition to the greenschist assemblage occurs adjacent to the large veins. Relict glaucophane grains are rare in the marble contact zone and adjacent to the large veins, suggesting nearly complete retrogression. Zone 2 is defined at 0.5 to 3.5 meters below the contact zone and is dominated by the greenschist facies overprint, but the protolith blueschist assemblage of glaucophane, paragonite, and epidote is discernable (Figure 2b). In this zone, the greenschist facies assemblage is restricted to foliation-parallel zones, likely indicating layer-parallel retrograde fluid infiltration [*Bröcker*, 1990]. Zone 3 is 3.5–6.5 meters below the contact and contains more of the HP-LT blueschist assemblage than the overprint mineralogy (Figure 2b). Zone 4 consists of a relatively fresh HP-LT blueschist assemblage of glaucophane, epidote, paragonite, garnet, ± quartz, ± titanite, ± rutile, ± pyrite that is found as a small exposure ~7 meters away from the base of *m*2 (Figure 2b). Greenschist facies overprinting is rare in this zone except adjacent to a large retrograde quartz vein. The extent of Zone 4 blueschists is difficult to discern because the outcrop becomes obscured in the lower-right corner of the photo in Figure 2a. However, Zone 1 assemblages re-appear ~4 meters below and to the right of the photo. Most rocks occurring more than ~15 meters below the base of *m*2 are dominated by Zone 1 assemblages. Interestingly, glaucophane relics are more common in the Zone 1 rocks distal to the marble contact, suggesting that retrogression was more intense within the contact zone than farther away. Preservation of the HP-LT assemblage was restricted to a narrow, ~10–15 m-wide, zone adjacent to the marble horizon contact. Similar mineral assemblage distributions occur near several other marble horizon contacts on Tinos [*Bröcker*, 1990] (Figure 1c).

5. Blueschist Preservation

[8] The well-defined mineral assemblage zonation pattern surrounding the enclave of HP-LT rocks suggests that retrograde fluids flowed primarily around these areas, rather than through them. Superimposed upon the broad mineral zonation pattern are minor variations that resulted from fluid flow along highly permeable, small-scale features like vein sets and metatuff layers (Figures 2a and 2b). Although many of the preserved HP-LT rocks in the Isternia outcrop appear to be within or near massive metabasalts, the intrinsic permeability contrasts between metabasalts and adjacent metasediments were not solely responsible for the lack of retrogression, as similar metabasaltic rock suites that occur far from marble horizons are completely overprinted. The intimate spatial association with marble units almost certainly had some influence on the preservation of HP-LT assemblages. Intense retrogression along marble contacts immediately adjacent to the blueschist enclaves suggests that the contacts served as high-flow conduits that were more permeable than the surrounding metasediments and metabasalts. The field relations and mineral assemblage distributions revealed by digital outcrop mapping suggest that the retrograde fluid flow was less intense adjacent to the contacts of some marble horizons. We postulate that regionally flowing, nearly pervasive, layer-parallel, greenschist facies fluids were drawn into the highly permeable contacts of the marble units, resulting in smaller fluid

fluxes in zones adjacent to the marble contacts due to deflections of flow paths around the adjacent zones and into the contacts. The relatively "dry" enclaves interacted with significantly smaller volumes of retrograde fluid and were sites of HP-LT mineral assemblage preservation. Fluid flow along lithologic contacts, associated veins, and more permeable metatuff layers resulted in nearly complete retrogression of rocks in the contact zone and the preservation of relatively unretrograded blueschist facies rocks within a few meters of the strongly overprinted contacts.

6. Modeling the Flow System

[9] Our interpretations based on field observations and digital outcrop mapping were tested using a steady state numerical model of two-dimensional, upward-directed flow. The model solved the standard Darcy flow equations for steady state fluid flow with no chemical reaction:

$$\mathbf{q} = -\frac{k}{\mu}\left(\nabla P_f + \rho_f g \nabla Z\right), \tag{1}$$

$$\frac{\partial\left(\phi\rho_f\right)}{\partial t} = 0 = -\nabla \cdot \left(\mathbf{q}\rho_f\right), \tag{2}$$

where $\mathbf{q}$ is the Darcy flux, k is permeability, μ is fluid viscosity, P_f is fluid pressure, ρ_f is the fluid density, g is gravitational acceleration, Z is a reference coordinate oriented parallel to layering that increases upward, ϕ is porosity, and t is time. The equations were solved with spectral-transform methods to increase model resolution using 769 grid points in the horizontal direction and 139 points in the vertical direction [*Bolton et al.*, 1997, 1999]. The flow region was isothermal and measured 1 km × 1 km with no-flux lateral boundaries. For simplicity, layering was oriented vertically. In order to model the effects of more-permeable marble contact zones, two narrow, elongate zones of high permeability (maximum of $\sim 10^{-17}$ m^2) were initially defined within the otherwise uniform flow region with fixed background permeability of $\sim 10^{-19}$ m^2 (Figures 3a and 3b). The 10^{-17} -10^{-19} m^2 permeability range is considered reasonable for deep metamorphic settings [*Hanson*, 1997; *Manning and Ingebritsen*, 1999]. The sides and edges of each high-permeability zone were nearly step-like in nature with half of the increase from background to maximum permeability occurring within 1.6 m. Permeablity and porosity were directly linked using the model of *Bolton et al.* [1997] and were held constant throughout the simulations. The permeability range of 10^{-17} -10^{-19} m^2 yielded a porosity range of 0.084% (background) to 0.28% (high-permeability zones). The fluid-pressure gradient was adjusted to produce a maximum pore velocity of 1 m/yr through conduits with maximum permeability ($\sim 10^{-17}$ m^2). This gradient was above hydrostatic, but somewhat below lithostatic, and falls within the range of many of *Hanson*'s [1997] model results for regional metamorphism. The fluid-pressure gradient was maintained using constant flux boundaries at the bottom (input) and top (output) of the flow region. Input fluid density was 1 g/cm^3, dynamic fluid viscosity was 10^{-3} kg/(m·s), and the fluid was considered incompressible. Other reasonable permeability and porosity scalings and fluid pressure gradients do not significantly change the overall flow patterns described below and in Figures 3a–3c.

[10] Representative boundary conditions were chosen for the HP-LT outcrop near Isternia primarily based on field data. *Avigad et al.* [1988] report that *m*2 is ~150 m thick in northwestern Tinos, so the spacing between centers of high-permeability zones was defined as 150 m. The actual average permeability within the marble unit was not known, so the background value was assumed for the area between the high-permeability zones. The structure and width (12m) of the high-permeability zones were based on field observations of the basal contact zone of the *m*2 marble horizon in the outcrop and include high-permeability contributions from the marble-schist contact zone as well as the associated veins and metatuff layers (Figures 2a and 2b).

[11] Model results indicate that fluid flow paths within the flow region are deflected into the contact

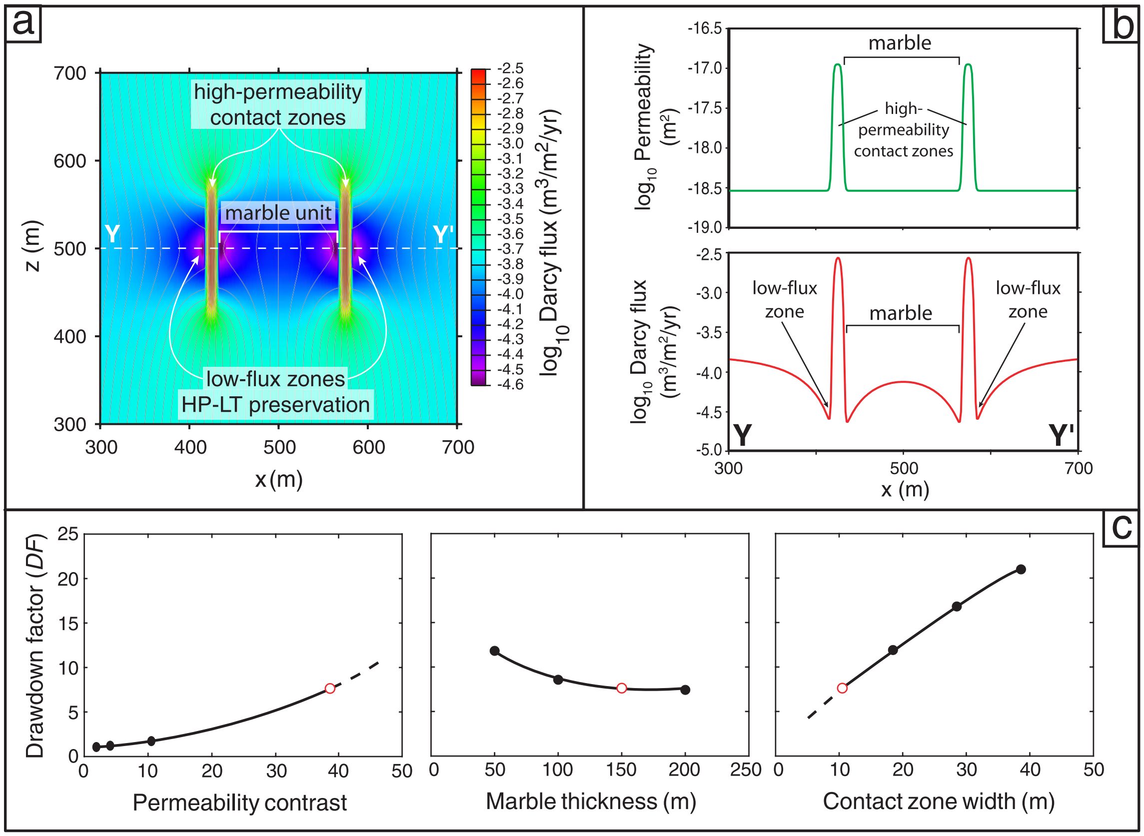

Figure 3. (a) Two-dimensional enlarged central region of Darcy velocity flow fields (i.e., Darcy flux magnitudes) and streamlines for steady state, upward-directed fluid flow through 1 km × 1 km isothermal flow region. Model parameters based on field observations from Isternia outcrop in Figure 2a. Two parallel, vertically oriented, 12-m wide, high-permeability (~10^{-17} m^2) zones defined within uniform flow region of lower permeability (~10^{-19} m^2) to simulate marble unit contact zones. Permeability in channels ~38 times higher than background. Fluid flux fixed (1.8×10^{-4} m^3/m^2/yr) at top and bottom of region to observe only the effects of high-permeability channels on fluid flow paths and fluxes. Spacing between channels set to 150 m, equivalent to actual thickness of *m*2 marble horizon adjacent to digitally mapped outcrop in Figure 2a. Fluxes within channels more than an order of magnitude larger than input flux. Note that low-flux zones, less than 20 m wide, develop adjacent to contacts of modeled marble unit. Darcy fluxes in low-flux zones ~8 times smaller than input flux. Focusing of fluids into highly permeable contact zones causes limited flow through adjacent enclaves where HP-LT mineral assemblages likely preserved from retrogression. (b) Cross sections (Y-Y′) for Darcy flux and permeability at z = 500 m in Figure 3a. Darcy fluxes in low-flux zones ~8 times smaller than input flux. Background permeability of ~10^{-19} m^2 steeply increases to ~10^{-17} m^2 in modeled contact zones. (c) Effects of model parameter variations on magnitudes of fluid flux in enclaves adjacent to high-permeability channels. Each parameter independently varied from base model in Figure 3a. Drawdown factor (DF) defined in equation (3). Increases in permeability contrast (equation (4)) and/or width of high-permeability contact zones results in smaller fluid fluxes (higher *DF* values) adjacent to modeled marble contacts. Conversely, increased spacing between channels (i.e., marble unit thickness) causes slight increases in flux adjacent to channels (lower *DF* values). Parameters used for Isternia outcrop base model in Figures 3a and 3b shown as open red circles.

zones, resulting in limited flow and low fluxes through the immediately adjacent regions (Figures 3a and 3b). Parameters such as contact zone width (i.e., width of each high-permeability zone), marble unit thickness (i.e., spacing between high-permeability zones), and permeability contrast between the background and the high-permeability contacts were independently varied in a series of steady state model runs to assess the effects of each parameter on the magnitude of fluid flow near the contact zones. In order to track changes in Darcy fluid flux in the low flux zones, a drawdown factor (*DF*) was defined:

$$DF = \frac{q_{input}}{q_{min}}, \tag{3}$$

where, q_{input} is the input flux and q_{min} is the minimum flux adjacent to contact zones. Higher *DF* values indicate lower fluid fluxes adjacent to contacts relative to the input flux and *DF* values approaching 1 indicate that fluid fluxes near contacts are approaching input values. The model permeability contrast between the high-permeability zones and the rest of the flow region was defined as

$$k_{contrast} = \frac{k^{contact-zone}}{k_{background}}, \tag{4}$$

where $k_{contrast}$ is the permeability contrast, $k^{contact\text{-}zone}$ is the variable permeability in contact zones, and $k_{background}$ is the fixed background permeability. The $k_{contrast}$ was modified by adjusting the permeability within the contact zones relative to the fixed background permeability. Variation of $k_{contrast}$ through a range of ∼1 to ∼38 causes *DF* values to increase from factors of ∼1 to ∼8 (Figure 3c). Thus, higher permeability contrasts draw more flow into the contact zones and decrease the flux in regions immediately adjacent to the zones. Variation of the width of the high-permeability zones from 12 to 40 meters likewise causes an increase in *DF* from factors of ∼8 to ∼21 (Figure 3c). Conversely, changes in the spacing of the contact zones (i.e., variations in model marble unit thickness) from 50 to 200 meters cause a gradual decrease in *DF* from factors of ∼12 to ∼8 (Figure 3c). Maximum *DF* values and the smallest relative fluid fluxes adjacent to contact zones are achieved with maximum permeability contrast, wide contact zones, and narrow marble units.

[12] The modeling results are consistent with the field observations and interpretations. Low-flux zones in the model are regions where HP-LT mineral assemblages would most likely be preserved, whereas the rest of the flow system is characterized by larger fluid fluxes and would have undergone retrogression (Figure 2b). Our numerical results for the Isternia outcrop suggest that the permeability contrast must be ∼20–50, or even higher, to cause significantly limited fluid fluxes (i.e., *DF* factors of ∼5–10) adjacent to the model conduits (Figure 3c). Large permeability contrasts can produce fluid fluxes within the low-flux regions that are nearly two orders of magnitude smaller than fluxes within the conduits and as much as 8 times smaller than the input flux (Figures 3a–3c). Presumably, these lower fluxes adjacent to the modeled *m*2 contact zones resulted in the preservation of blueschists in the Isternia outcrop seen in Figure 2b. The model flow system strongly suggests that the observed preservation of HP-LT mineral assemblages in 10–15 m enclaves adjacent to contacts of thick marble horizons was the result of channelization of fluid flow along more permeable marble unit contacts. Contact-parallel fluid flow not only influences the distribution and preservation of mineral assemblages in metamorphic terranes, but may also have important implications for regional fluid flow paths in subduction zones.

7. Conclusions and Implications

[13] Fluid flow paths in subduction zones have long been the source of debate. Field evidence is abundant that metamorphic fluids interacted with HP-LT metamorphosed crust both during subduction and exhumation in Greece. However, most isotopic and petrologic studies indicate no evidence for large-scale fluid flow in the Cyclades, leading to suggestions that flow must have been limited or extremely channelized. Pervasive retrogression of regionally extensive rock packages, as observed on Tinos, requires large-scale fluid flow during exhumation, yet until now, no regional-scale retrograde fluid conduits had been identified. Digital outcrop mapping of mineral assemblages in the HP-LT rocks of Tinos and numerical modeling of the flow system indicate that some lithologic contacts and associated veins served as major conduits for regionally moving fluids. The HP-LT terrane exposed on Tinos underwent near pervasive retrograde fluid infiltration during exhumation. Con-

tacts between large marble horizons and surrounding metasedimentary and metaigneous rocks were highly retrograded and commonly fractured, and are inferred to have been zones of elevated permeability. We conclude that fluids were preferentially channelized into these zones of high permeability and high fluid flux. As a consequence, HP-LT assemblages were preserved in the directly adjacent low-flux regions. Evidence for a significant, contact-parallel component of metamorphic fluid flow provides important insight into the nature of fluid flow pathways at intermediate depths in subduction zones. The reported absence of stable isotopic fluid alteration signatures (either prograde or retrograde) in most HP-LT terranes may be the result of localization of regionally flowing fluids in a layer-parallel/fracture flow system within the subducting slab and downgoing continental crust. Our digital mapping and modeling strongly suggest that lithologic contacts and associated fractures/veins are one of the elusive, major flow channels for retrograde metamorphic fluids in subduction zones. This field-based identification of flow conduits in the Attic-Cycladic Blueschist Belt provides some measure of reconciliation between the hitherto contrasting views of fluid flow during subduction, metamorphism, and exhumation of HP-LT terranes.

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