OCCURRENCE AND SIGNIFICANCE OF SERPENTINITE-HOSTED, TALC- AND AMPHIBOLE-RICH FAULT ROCKS IN MODERN OCEANIC SETTINGS AND OPHIOLITE COMPLEXES: AN OVERVIEW

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ABSTRACT

This paper reviews the occurrence and significance of talc- and amphibole-rich fault rocks developed in mafic-ultramafic sequences and evaluates their role in deformation and alteration of the oceanic lithosphere from different tectonic settings (from spreading mid-ocean ridges up to orogenic belts). Recently, talc and amphibole-rich fault rocks have been sampled and studied from detachment fault surfaces along slow and ultra-slow spreading mid-ocean ridges, and constraining the conditions of deformation and strain localization during the evolution of oceanic core complexes. These rocks are documented not only in oceanic core complexes, but also in other oceanic fracture zones where ultramafic rocks are exposed on the seafloor, while only few occurrences have been reported in ophiolite sequences. Samples recovered in situ in oceanic settings record heterogeneous deformation (crystal-plastic to cataclastic) under greenschist-facies conditions and are commonly restricted to localized shear zones (< 200 m) and are associated with intense talc-amphibole metasomatism. The presence of mechanically weak minerals, such as talc, serpentine and chlorite, may be critical to the development of such fault zones and may enhance unroofing of upper mantle peridotites and lower crustal gabbroic rocks during seafloor spreading. Talc in particular may be influential in lubricating and softening mylonitic shear zones and can lead to strain localization and focused hydrothermal circulation along such faults. The rheology of these rocks, and its evolution during dehydration reactions could play an important role also in subduction-zone processes and during the formation of ultramafic orogenic belts. Here, we review the occurrence and significance of talc- and amphibole-rich fault rocks in different tectonic settings on the seafloor and evaluate their role in deformation and alteration of the oceanic lithosphere.

INTRODUCTION

Fault rocks consisting of varying proportions of talc, amphibole and chlorite that appear as distinctly light- to white-colored rocks with a soapy feel, similar to "steatites" or "soapstones" in Alpine peridotite terrains, have increasingly been documented at slow- and ultraslow spreading ridges and in magma-poor margins. They are commonly related to processes of tectonic uplift and exposure of atypical sections of the oceanic lithosphere and to the formation of oceanic core complexes (OCCs) and often are key elements of many oceanic core complexes (OCCs) and often record a deformation and metamorphic history that is distinct from the underlying basement rocks (Fig. 1 and Table 1; Miranda E.A. et al., 2002; Reston et al., 2002, Escartín at al., 2003; Schroeder and John, 2004; Cheadle et al. 2005; Harigane et al., 2005; Boschi et al., 2006a).

Extreme extension of oceanic lithosphere during seafloor spreading creates oceanic core complexes (OCCs) interpreted to be analogous to metamorphic core complexes in continental settings (e.g., Crittenden et al., 1980; Wernicke, 1981) and defined by broad, elevated massifs (few tens of kilometers across) where deep crustal and in some cases upper mantle rocks have been unroofed and uplifted (Karson, 1990; Mutter and Karson, 1992; Tucholke et al., 1998; Reston et al., 2002; Blackman et al., 2004; Karson et al., 2006). Their formation is generally attributed to a system of large-scale, low-angle normal (detachment) faults or shear zones marked by spreading-parallel corrugations and finer scale striations on the arched surfaces of the OCCs (Cann et al., 1997; Tucholke et al., 1998; Reston et al., 2002; Okino et al., 2004; Karson et al., 2006) thought to; in some cases OCCs may be associated with varying degrees of magmatic accretion (e.g., Karson and Dick, 1983; Karson, 1990; Dick et al., 1991; Mutter and Karson, 1992; Tucholke et al., 1998; Ranero and Reston, 1999; Escartín et al., 2003).

As in continental metamorphic core complexes, oceanic detachment faults expose a diverse suite of rock types that

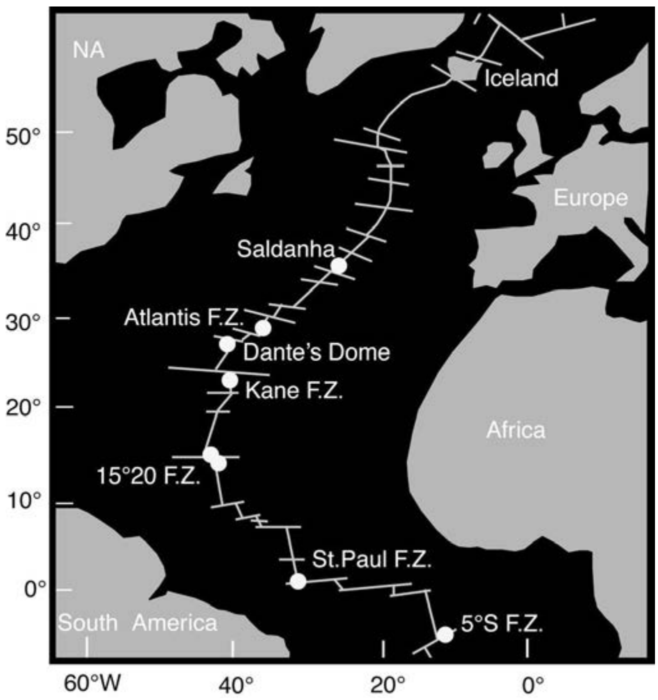

Fig. 1 - Location of talc and amphibole schist occurrences along the MAR.

Table 1 - Fault rock locations in oceanic and continental settings.

Location	Comments and descriptions	References
Detachment Areas		
15°45'N (MAR)	Talc and amphibole schist along the detachement surface; shear zone < 100 m.	Macleod et al., (2002); Escartìn et al., (2003).
Kane core complex (23°30'N; MAR)	Fault rocks (talc- and amphibole-rich) on the detachement surface with cataclastic deformation; brittle shear zone <100 m.	Cheadle et al., (2005).
Dante's Dome (26°35'N; MAR)	Loose clasts from Alvin Dive 440. Amphibole- and chlorite-rich serpentinites and sheared clay-rich mylonitez serpentinite.	Tucholke et al., (2001).
Atlantis Massif (30°N; MAR)	Talc and amphibole schist along the detachement surface for at least 3 km in the tectonic transport direction; shear zone < 100 m.	Schroeder et al., (2004); Boschi et al., (2006).
Saldhana Massif (36°34'N; MAR)	Metagababbros, serpentinites and talc-bearing serpentinites along the upper surface of the massif.	Miranda et al., (2002).
Rifted detachment, 5°S (MAR)	Sheared mylonite serpentinites along the detachment.	Reston et al., (2002).
Atlantis Bank (SWIR)	Thin layer of fault rocks over footwall (<100 m). Main shear zone associated with detachment up to 500 m thick.	Miranda et al., (2002).
Godzilla Mullion (Philippine Sea)	Metagabbros, mylonitic serpentinites and talc schist over the footwall.	Harigane et al., (2005).
Moresby Seamount (Woodlark basin; Papua New Guinea)	Talc-chlorite-serpentine fault gouge along the fault.	Floyd et al., (2001); Taylor and Huchon, (2002).
Oceanic Fracture Zones and nearby areas		
15°20N F.Z. (MAR; ODP Leg209)	200 m static talc alteration of serpentinites.	Paulick et al., (2004); Bach et al. (2004).
St Paul F.Z., (0.6°S; MAR)	Talc-rich breccia dredged at the outer corner.	D'Orazio et al., (2004).
Conrad F.Z., (55.7°S; MAR)	Talc schist dredged at inside corner of ridge-transform intersection.	D'Orazio et al., (2004).
Islas Orcadas F.Z., (6°E 54°S; SWIR)	Dredged metasomatic ultramafic rocks.	Kimball et al., (1985).
Ocean Continental Transition Zones and Continental Settings		
Appennine (Italy)	Talc, chlorite, saponite formation pre-emplacement of the serpentinites.	Montanaro, (1930); Repossi, (1942); Aletti, (1959).
Appalachians (Virginia and Vermont, USA)	Metasomatic ultramafic intrusions and talc deposits.	Hess, (1933).
Humphreys, Fresno Couty, California (USA)	Metasomatic talc- and amphibole-rich serpentinite nodules.	Pabst, (1942).
Ipanema (southeastern Brazil)	Talc and amphibole metasomatism of ultramafic bodies.	Angeli and Choudhuri, (1985).
Alps (Val Malenco; Italy)	Serpentinite-hosted talc deposits.	Beaulieu, (1985).
Cima di Gagnone, (Valle Verzasca; Switzerland)	Metasomatism of ultramafic lenses-shaped masses.	Pfeifer, (1987).
North Cascades (Washington; USA)	Metasomatism during imbricate thrusting of an ophiolite.	Miller, (1988).
Alps (Austria)	Talc formation related to the ultramafics of the Penninic unit.	Prochaska, (1989)
Pennsylvania Piedmont (USA)	Talc schist and talc deposits in the State-line serpentinite along shear zones.	Gates, (1991).
Josephine Ophiolites (California; USA)	Talc-amphibole metasomatism rimmed serpentinites along oceanic fault.	Coulton et al., (1995).
Western Iberia Margin	Cataclastic breccia and serpentinite fault gouge.	Whitmarsh et al., (1996); Beslier et al., (2001); Manatschal (2004)
Eastern Desert (Egypt)	Talc fels, chlorite-rich talc fels and tremolite-actinolite-rich talc fels; ultramafic protolith. Metasomatism after emplacement of ultramafic rocks.	El-Sharkawy, (2000).
Altermark province (Norway)	Talc metasomatism of ultramafic lenses.	Karlsen et al., (2000).
Alps (Italy)	Formation of talc-rich serpentinite mylonites during the exhumation to the seafloor.	Desmurs et al., (2001).
Franciscan Complex (California; USA)	Talc-amph metasomatism in subduction zone.	King et al., (2003).
New Caledonia	Talc-rich zone separating ultramafic pod from host rocks.	Fitzherbert et al., (2004).
Trodos Ophiolites (Cyprus)	Amph-chlorite metasomatism along oceanic fault.	Cann and McCaig, (2006).
Sivas Basini (Turkey)	Ultramafic-hosted talc occurences.	Yalçin and Bolzkaya, (2006)

are derived from different lithospheric levels and which record varying magmatic/tectonic histories and conditions of metamorphism (e.g. Gillis et al., 1993; Kelley et al., 1993; Cannat et al., 1997; Karson and Lawrence, 1997; Karson, 1998; 1999; Taylor et al., 1999; Dick et al., 2000; Bach et al., 2004). Some complexes record an early high-temperature deformation and metamorphism [e.g. at the Atlantis Massif (MAR 30°N) and at the Kane Megamullion core complex (MAR 23°30'N); Schroeder and John, 2004; Cheadle et al., 2005; Tucholke et al., 2005; Fig. 1] or may root in melt-rich zones in gabbroic crust [e.g., Atlantis Bank, Southwest Indian Ridge (SWIR), the Site 735B and 5°S F.ZOCC near the 5°S Fracture Zone on the MAR; Dick et al., 1991; 2000; Reston et al., 2002]. Others, such as the MAR 15°45'N core complex, show localized deformation zones in relatively cold, serpentinized mantle peridotites, with no evidence for significant precursor high-temperature metamorphism and deformation (MacLeod et al., 2002; Escartín et al., 2003). Although in many areas direct observation and sampling of the detachment surfaces and associated fault rocks are hindered by the presence of rubble and sediments, detachment fault zones coupled with discontinuous shear zones seem to be characterized by highly localized deformation at relatively low temperature, in greenschist-facies conditions, producing talc and amphibole-rich fault rocks (MacLeod et al., 2002; Escartín et al., 2003; Schroeder and John, 2004; Boschi et al., 2006a). Thus, these rocks have received little attention in the literature, but may provide an important record of deformation and metasomatism associated with the exhumation of lower crustal/upper mantle sequences on the seafloor. In addition, their occurrences, even in small amounts, can substantially weaken the lithosphere and enhance the displacement along the fault surfaces that could be as much as a few tens of kilometers (Karson et al., 2006).

Similar fault rocks have also been documented not only in oceanic core complexes, but also in: 1) other oceanic fracture zone settings where ultramafic rocks are exposed on the seafloor (e.g., Kimball et al., 1985; Taylor and Huchon, 2002; Miranda J. M. et al., 2002; Bach et al., 2004, D'Orazio et al., 2004; Table 1); 2) in ultramafic bodies in fold-thrust belts and in subduction zones (e.g., Montanaro, 1930; Hess, 1933; Pabst, 1942; Repossi, 1942; Alietti, 1959; Angeli and Choudhuri, 1985; Pfeifer, 1987; Miller, 1988; Prochaska, 1989; Gates, 1991; Coulton et al., 1995; El-Sharkawy, 2000; Desmurs et al., 2001; King et al., 2003; Cann and McCaig, 2005; Yalçin and Bolzkaya, 2006; Table 1). Such findings indicate that the formation of metasomatic talc-amphibole assemblages in mafic-ultramafic sequences is not restricted to active oceanic settings and that it can also occurs during the tectono-metamorphic reworking of ophiolites in orogenic settings.

In this paper we review the occurrence of talc- and amphibole-rich metasomatic rocks and their geological settings in modern marine environments and in ophiolites (i.e., the association with long-lived fault zones). In addition, we focus on the genesis and on the nature of deformation recorded in talc- and amphibole-rich fault rocks sampled in modern long-lived oceanic fault zones and we evaluate their role in deformation and alteration of the oceanic lithosphere.

OCCURRENCES AND GEOLOGICAL SETTINGS

Present oceanic fracture zones and detachment shear zones

Few OCCs have been sampled in detail in modern oceans, but rocks recovered by dredge and submersible invariably include gabbros and serpentinized peridotites, mylonitic gabbros, dikes, plagioclase-impregnated ultramafic rocks, diabases, monomineralic chlorite-rich rocks, minor basalt and basaltic debris (Tucholke et al., 2001 and references therein). This heterogeneous suite of rocks is not representative of lithologies typically found in stratiform ophiolites sequences (Penrose Conference Participants, 1972; Moores et al., 1984) and therefore probably represents the locus of distinct thermal, tectonic and fluid processes during the evolution of the oceanic lithosphere.In the absence of significant magmatic construction, they may essentially define the plate boundary for as much as 2 m.y. (Karson et al., 2006).

The Atlantis Massif (MAR 30°N; Fig.1) is one of the most comprehensively studied OCCs along the MAR and the detachment shear zone documented on the south wall of the massif is one of the best exposed and clearly defined structures of its kindexamples known today (Boschi et al., 2006a; Karson et al., 2006). Information related to the initiation, structural and metamorphic history of the detachment shear zone is recorded in the composite exposed rocks of this unit. Focused sampling revealed a range of intensely deformed, metamorphosed and metasomatized rocks that record a protracted history of high strain and fluid-rock interactions through decreasing temperatures. Strongly foliated talc- and amphibole-schists within the detachment shear zone (Figs. 2 and 3) can be traced continuously for at least 3 km in the tectonic transport direction and grade structurally downward into more massive basement rocks (Boschi et al., 2006a; Karson et al., 2006).

Other occurrences of fault rocks along major subhorizontal detachment shear zones (up to 200 m thick) have been reported from numerous areas along the slow- and ultraslow spreading ridge system, for example at the MAR 15°45'N (Escartín at al., 2003), at the Kane core complex (23°30'N; Karson and Lawrence, 1997; Cheadle et al., 2005), at the MAR 5°S (Reston et al., 2002), at the Dante's Dome (26°35'N Tucholke et al., 2001), at the Atlantis Bank (SWIR; E.A. et al., 2002) and at the Godzilla Mullion (Philippine Sea; Harigane et al., 2005; Fig. 1 and Table 1). Overall, the fault rocks show an ultramafic and/or gabbroic protoliths with varying degrees of metasomatic alteration to talc-, amphibole-, and chlorite-bearing assemblages (Tucholke et al., 2001; Miranda E.A. et al., 2002; Reston et al., 2002; Taylor and Huchon, 2002; Escartín at al., 2003; Schroeder and John, 2004; Cheadle et al. 2005; Harigane et

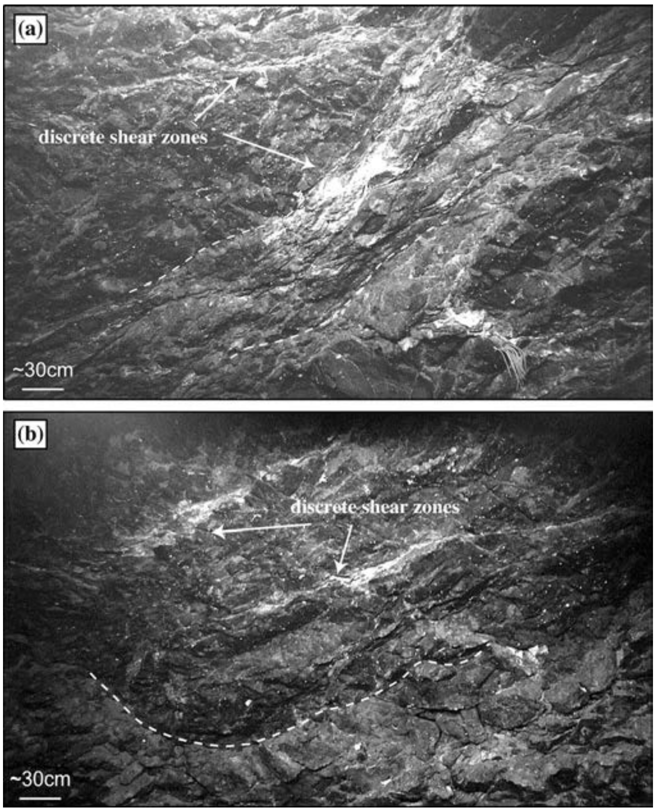

Fig. 2 - Examples of outcrops of the detachment shear zone (DSZ), near the top of the south wall of the Atlantis Massif, showing discrete anastomosing mylonitic shear zones cutting the serpentinite foliation and containing metasomatic mineral assemblages.

al., 2005; Boschi et al., 2006a). Talc and amphibole are the most abundant mineral phases (± chlorite, oxides and serpentine) and are present in varying inverse proportions in rocks showing heterogeneous, crystal-plastic to cataclastic deformation (Fig. 3).

Further occurrences of talc-bearing serpentinites have been reported in other areas that may not directly be connected to the development of a major detachment fault system, but where ultramafic rocks are exposed on the seafloor near fracture zones, such as at the15°20°N Fracture Zone (MAR; Bach et al., 2004), at the Conrad Fracture Zone (MAR; D'Orazio et al., 2004) and at the Islas Orcadas Fracture Zone (SWIR; Kimball et al., 1985; Table 1). Abundant talc-rich rocks (described as steatites) were also recovered at the Saldahna Massif (MAR, 36°34'N), a serpentinite dome within the non-transform offset (NT05) zone between the AMAR and FAMOUS second-order ridge segments south of the Azores (Miranda J.M. et al., 2002; Dias and Barriga, 2006). Although no detachment fault has yet been identified, emplacement of the Saldahna Massif has been attributed to complex tectonic processes at non-transform offsets, possibly involving detachment faulting with similar mechanisms similar to those at inside corner highs (Miranda J.M. et al., 2002; Dias and Barriga, 2006). In general, most of these occurrences (Kimball et al., 1985; Miranda J.M. et al., 2002; Bach et al., 2004; D'Orazio et al., 2004; Dias and Barriga, 2006) even if not directly be connected to a major detachment fault, seem to be related to stretching of the lithosphere, faulting, and associated hydrothermal circulation during the seafloor spreading. In addition, drilling of serpentinized mantle rocks in the Iberia Abyssal Plain at Site 897 (Beslier et al., 1996) suggested that the peridotite ridge is a major feature that borders the margin over more that 250 km along the ocean/continent transition. Beslier et al. (1996) indicated that the serpentinized peridotites underwent a continuum of deformation at decreasing temperature and decreasing pressure, compatible with mantle dome uplift beneath a continental rift zone. Moreover, they highlighted the importance of low-temperature deformation associated with an intense hydrothermalism during the late evolution of the mantle. Hydrothermalism is indeed responsible for the progressive serpentinization of the mantle and also aids fracturing of the rocks: an increasing proportion of serpentine, which is a highly ductile material even at low temperatures, changed the rheological behavior of the rocks progressively from brittle to ductile during the further extension and the late emplacement stages of the mantle on the seafloor (Beslier et al., 1996). In addition, accordingly, Taylor and Huchon (2002) reported the occurrence of talc-chlorite-serpentine gouge as an important weakening mechanism in low-angle normal faults at the transition from rifting to spreading in the Woodlark Basin (Papua New Guinea).

Talc-rich rocks may also be the result of direct precipitation from modified seawater fluids enriched in Si or Mg by interaction with sediments or basement rocks as reported from the St. Paul Fracture Zone (D'Orazio et al., 2004),

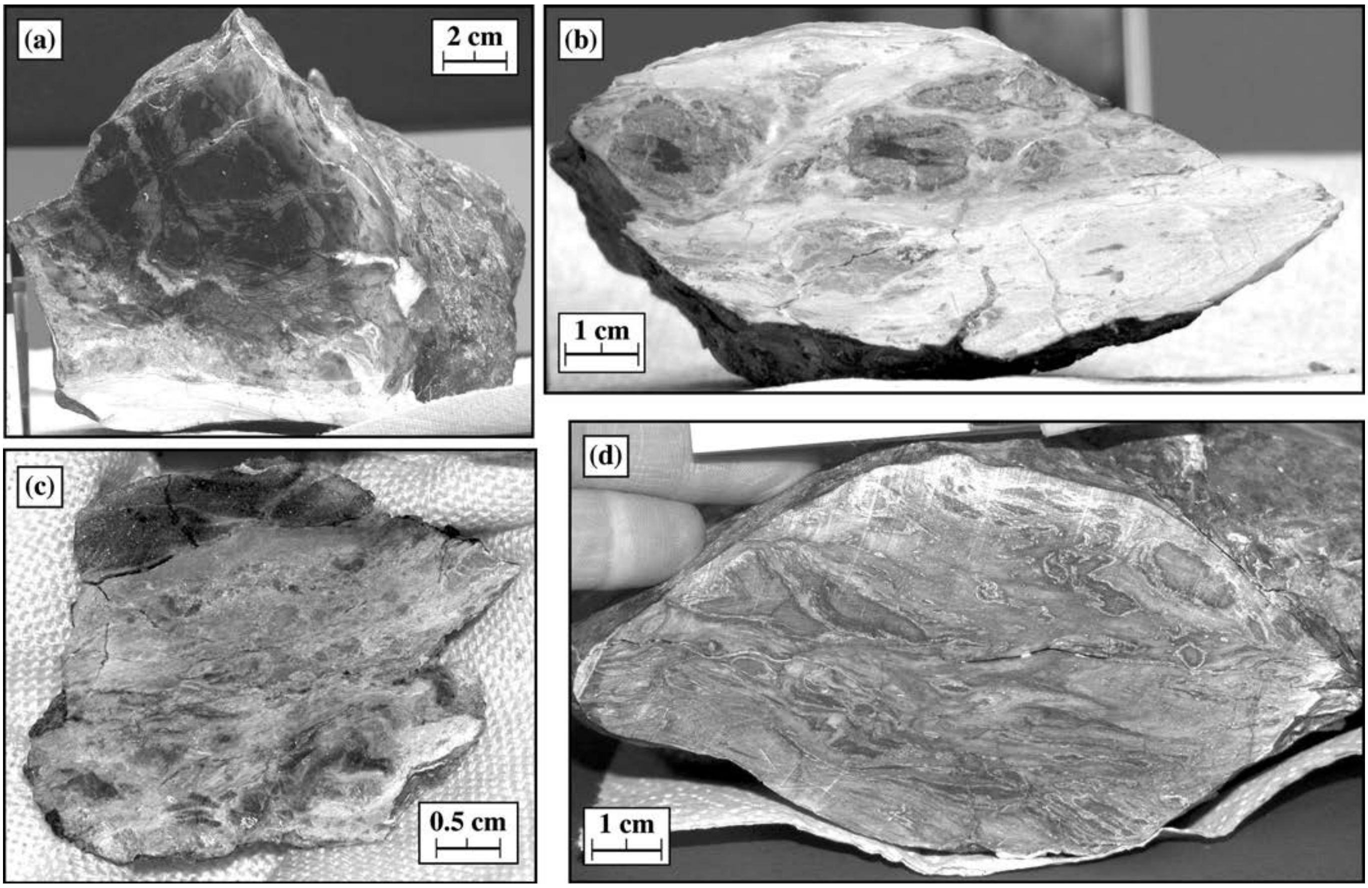

Fig. 3 - Example of typical fault rocks from the Atlantis Massif (30°N; MAR). These samples show a variable and progressive deformation to metasomatic talc- and amphibole-schists. (a) Oxidized porphyroclastic serpentinite with thin metasomatic rim (or alteration front) of talc-amphibole metasomatism. A narrow band of highly foliated talc schists (white area) is seen on the bottom of the sample (sample 3873-1317); (b) Metasomatic talc-amphibole-rich bands (light colored domains) enclosing lenses of oxided serpentinite (dark domains) (sample 3873-1124); (c) heterogeneous mylonitic to porphyroclastic porfiroclastic texture of a talc-rich fault rock (sample 3863-1204) and; (d) typical talc-amphibole schist showing heterogeneous high strain crystal-plastic textures (sample 3645-1225). See Boschi et al. (2006a) and Karson et al. (2006) for sample locations and descriptions.

from the Guaymas Basin (Gulf of California, Lonsdale et al., 1980), from the Tiornes Fracture Zone FZ (associated with anhydrite; 66°36'N, Iceland; Hannington et al., 2001) and from Archean ocean water (Costa et al., 1980).

Ophiolite sequences and ultramafic bodies in fold-thrust belts

Ophiolite tectonic units are a common feature of many orogenic belts representing a witness of the oceans subducted/obducted at convergent margins. Depending on the PT-path followed, ophiolites can be represented by well-preserved and not metamorphosed mantle-crust oceanic sequences as well as by disrupted and fragmented metamorphic lenses embedded in marbles, schists, gneiss and other metamorphic rocks.

Well preserved ophiolite sequences, as subaerial exposures of oceanic lithosphere, potentially provide important details on the nature of extensional processes operating in various oceanic spreading regimes at crustal and upper mantle depths that cannot be directly examined in the modern oceans. Although ophiolite emplacement typically results in some degree of deformation and associated metamorphism, the variety of stratigraphic levels exposed in ophiolites provides an essential complement to the oceanographic database. The recognition of faults and veins related to subseafloor spreading processes in ophiolites, and their distinction from similar features possibly developed during the orogenic evolution, is of critical importance to the use of ophiolites as analogs for oceanic lithosphere. Oceanic faulting has been increasingly documented in ophiolites, including the Troodos Ophiolite (Varga, 1991; Cann and McCaig, 2005), the Lizard Ophiolite (Gibbons and Thompson, 1991), the Kızıldag Ophiolite (Dilek et al., 1991), the Josephine Ophiolite (Alexander and Harper, 1992; Alexander et al., 1992; Coulton et al., 1995), and in a number of ophiolite sequences in the Apennines and Alps (Abbate et al., 1980; Hoogerduijn Strating, 1988; Treves and Harper, 1994; Manatschal et al., 2000; Desmurs et al. 2001). Talc and amphibole metasomatism associated with oceanic faulting and comparable to present-day structure of a slow-spreading ridges to date have been reported by Coulton et al. (1995), Desmurs et al., (2001), and Cann and McCaig (2005). The paucity of talc- and amphibole-rich fault rocks in ophiolite sequences directly connected with seafloor spreading indicates either that they are volumetrically negligible or that they have been reactivated, reworked and deformed during later tectonic activity. Alternatively, although preserved, such outcrops may have lost their original continuity and they are thus probably underestimated or considered as local features.

In several instances, carbonate-serpentinite breccias, called "ophicalcites", are reported in ophiolitic sequences and are believed to have formed during hydrothermal and tectonic processes associated with serpentinization in fracture zone environments (Lemoine, 1980; Cortesogno et al., 1981; Lagabrielle et al., 1982; Weissert and Bernoulli, 1985; Bernoulli and Weissert, 1985; Früh-Green et al., 1990; Driesner, 1993; Trommsdorff et al., 1993; Treves and Harper, 1994; Treves et al., 1995; Pozzorini and Früh-Green, 1996; Lagabrielle and Lemoine, 1997), or during exhumation of subcontinental mantle along passive margins (Beslier et al., 1996; Desmurs, et al., 2001; Bernoulli et al., 2003). Ophicalcites are ophiolitic breccias, predominantly serpentinite-hosted, and are either stratigraphically interposed between serpentinites and other ophiolitic breccias or basalts, or occur directly between serpentinites and pelagic sediments (Lemoine, 1980; Cortesogno et al., 1981; Weissert and Bernoulli, 1985; Bernoulli and Weissert, 1985; Bernoulli et al., 2003). The serpentinitic and gabbroic fragments of the ophicalcite commonly record ductile to cataclastic deformation associated with hydrothermal alteration.

Cortesogno et al. (1981) suggested that the "Levanto Breccia " at Cava dei Marmi (Northern Apennines, Italy) is an example of ophicalcite that consists of fractured serpentinite hosting a complex network of calcite (± hematite ± chlorite ± tremolite ± talc) veins of oceanic origin. It is important to note that Cortesogno et al. (1981) recognized a deformational phase, preceding the genesis of the Levanto ophicalcite, characterized by an intense metasomatism that produced talc, tremolite and chlorite mineral assemblages in the ultramafic rocks (i.e. talc schist) and tremolite, chlorite and titanite in the gabbros (i.e. amphibole schist). This stage of the process by which the Levanto Breccia were formed could correspond to the formation of the talc- and amphibole-rich fault rocks during the Jurassic oceanic spreading. We suggest that part of the ophicalcites sampled in ophiolitic sequences may previously have been talc- and amphibole-rich fault rocks formed along oceanic detachments that have been later dismembered and reworked into the ophicalcite sequences. This is in agreement with Treves and Harper (1994) that interpreted the Levanto ophicalcite as fault rocks formed during the final unroofing of serpentinized upper mantle along a ductile to brittle detachment zone. In addition, several authors (Montanaro, 1930; Repossi, 1942; Alietti, 1959) reported occurrences of talc bodies inside serpentinites of the Northern Appennine.

Serpentinite-hosted talc-rich rocks have also been reported in other ultramafic bodies and/or dismembered ophiolites from metamorphic terranes, such as in southeastern Brazil (Angeli and Choudhuri, 1985), in Val Malenco, Italy (Beaulieu, 1985), in Valle Verzasca, Switzerland (Pfeifer, 1987), in the North Cascades of Washington (Miller, 1988), in the Austrian Alps (Prochaska, 1989), in the Pennsylvania Piedmont (Gates, 1991), in Eastern Desert of Egypt (El-Sharkawy, 2000), in the Franciscan Complex, California (King et al., 2003), in the Urals (Nimis et al., 2004), in New Caledonia (Fitzherbert et al., 2004), and in the Sivas Basin, Turkey (Yalçin and Bozkaya, 2006; Table 1). In most of these examples, talc- and amphibole-rich rocks have been formed during the regional metamorphic evolution of these terranes by metasomatism of serpentinite bodies in contact with silica-rich crustal rocks ("blackwall-type" settings). However, although not related to oceanic mantle exhumation, talc and amphibole mineralization is concentrated in faults and fractures and in the rims of the ultramafic bodies.

In some cases talc-rich bodies hosted by metamorphic ophiolites are well known to contain economically viable concentrations of talc. About 40% of the present worldwide production of talc comes from the transformation of serpentinite into a mixture of talc and magnesium carbonate, commonly called soapstones. This type of deposit is relatively common and widely distributed in ultramafic belts (e.g., in Austria, Canada, Egypt, Finland, Italy, Norway, Quebec, Turkey, and USA). Talc deposits associated to serpentinized ultramafic-hosted rocks seem to be formed either through processes of regional metamorphism and thrust faulting of serpentinized ultramafics (Beaulieu, 1985; Salem, 1992; O'Hanley, 1996; Karlsen et al., 2000), either through processes of contact metamorphism and granitic pluton intrusion (Beaulieu, 1985 and reference therein), or they could be linked with the tectonic activity at the oceanic spreading ridge (Alietti, 1959).

Due to the lack of detailed petrographic and geochemical studies on talc- and amphibole-rich rocks in ophiolite sequences, in the following sections we present some considerations about the origin and the style of deformation of fault rocks recovered only in present oceanic fracture zones.

ORIGIN OF TALC- AND AMPHIBOLE-RICH FAULT ROCKS

Hess (1933) studied more than a hundred talc deposits in the Appalachian serpentinites and defined the term "steatization" as the hydrothermal-metasomatic alteration of ultrabasic rocks to form talc-soapstones. The succession of mineral assemblages of hornblende, actinolite, chlorite, talc, and carbonate is characteristic of steatization, where hornblende is the high temperature end member, and talc and carbonate are the relatively low temperature end member of the series.

In hydrothermally metamorphosed oceanic rocks, assemblages of talc, calcic amphibole and chlorite are common and generally form at a broad range of temperatures under greenschist-facies conditions below 500°C, as replacement of primary and secondary mafic minerals during multistage water/rock interaction or as direct precipitation during mixing of hydrothermal fluids and seawater (Boschi et al., 2006a and reference therein).

Talc-rich fault rocks sampled in present oceanic fracture zones show clear petrographic and geochemical relationships with serpentinized ultramafic protoliths (Escartín at al., 2003; Bach et al., 2004; Harigane et al., 2005; Boschi et al., 2006a), such as relics of Mg-chromite with distinct Cr and Ni concentrations typical of peridotites embedded into the talc-rich matrix (e.g., Escartín at al., 2003). At the Atlantis Massif, progressive deformation and formation of talc schist is particularly evident in serpentinite samples (Figs. 3 and 4a, b, c, d), in which lenses of relict serpentinite are surrounded by white, sheared irregular domains that consist of metasomatic, talc-rich mineral assemblages (Boschi et al., 2006a). Furthermore, pervasive and static talc alteration reported by Bach et al. (2004) overprints the previous serpentinization but commonly preserves the original serpentinite microtextures of the altered harzburgite. In all studied samples (Escartín at al., 2003; Bach et al., 2004; Boschi et al., 2006a), talc occurs either as a replacement product of groundmass serpentine, or together with tremolite ± chlorite as alteration product of bastite pseudomorphs after orthopyroxene.

The formation of talc-rich rocks and the replacement of serpentine by talc is a metasomatic process that indicates substantial mass transfer of Mg, Fe, and Si and that can be summarized by the simple reaction:

Serpentine + $2SiO_2$ = Talc + H_2O

which proceeds to the right if the silica activity of the fluid increases and/or if the water activity is lowered. Such a reaction is generally considered a prograde reaction taking place in the presence of SiO_2-rich fluids at temperatures of about 300-350°C (at low pressure, Evans and Trommsdorff, 1970; Bach et al., 2004; Manning, 2004). Accordingly, isotopic studies and temperature calculations for the Atlantis Massif talc-rich rocks indicate that localized talc metasomatism is characterized by a temperature range of 330-450°C, low fluid-rock ratios and it was controlled by the access of seawater-derived fluids to rocks of mafic compositions (Boschi et al., 2006b).

In contrast to the talc-rich rocks, alteration to amphibole-rich assemblages has commonly obliterated the primary textures and precursor mineral parageneses, preventing an unequivocal petrographic determination of the protoliths (Figs. 4e, f, g ,h); however, geochemical data point to a gabbroic or pyroxenitic protolith (Boschi et al., 2006a). The amphibole-rich rocks sampled in present oceanic fracture zones show alteration textures that are distinct from the talc-rich rocks and consist of well-crystallized, elongate and often aligned amphibole that wraps around lenses and patches of amphibole ± chlorite that resemble deformed and elongate pyroxene porphyroclasts (Boschi et al., 2006a). Talc is either typically absent in these rocks or occurs only locally together with fine-grained needles of amphibole and chlorite as pseudomorphs of orthopyroxene porphyroclasts.

The close spatial association of talc-rich (with ultramafic protolith) and amphibole-rich rocks (with mafic protolith) along the detachment shear zone at the Atlantis Massif suggests that they are strictly related (Boschi et al., 2006a; 2006b). Theoretical geochemical models indicate that, at 350°C and 500 bars, mafic rock-seawater reactions form hydrothermal fluids that are many orders of magnitude higher in silica and lower in pH than hydrothermal fluids produced by reaction of seawater with ultramafic rocks (Wetzel and Shock, 2000). Hydrothermal reaction between gabbro and seawater under greenschist-facies conditions along the detachment zone transform pyroxene and plagioclase in the gabbros to chlorite, amphibole, and talc (forming the amphibole schist), releasing silica and causing Si metasomatism and talc formation in the neighboring serpentinites (forming the talc schist; Boschi et al., 2006a, 2006b; Fig. 5a).

By contrast, Escartín et al., (2003) do not observe gabbroic outcrops in the detachment areas and proposed that the Si-rich fluids responsible for the intense metasomatism are the result of interaction between hydrothermal fluid and peridotites (at temperatures > 350°C) or/and basalt in the surrounding areas (Fig. 5b).

DEFORMATION MECHANISMS RECORDED BY FAULT ROCK ALONG THE DETACHMENT ZONES

Deformation along detachment shear zones is intimately connected to the tectonic evolution of the core complex and to the evolving geometry of the shear zone. A number of structural and tectonic studies interpret detachment faults as cutting the entire thickness of the lithosphere and soling-out either at the brittle-plastic transition (Tucholke et al., 1998; 2001), either at a melt-rich hot zone near the gabbro-dike transition (Dick et al., 1991), or along an alteration front horizon at relatively shallow depth within the brittle lithosphere (MacLeod et al., 2002; Escartín et al., 2003). According to evolving shear-zone models across the brittle-plastic transition (Tucholke et al., 1998; 2001), detachment faulting and associated brittle deformation occur in the upper levels of a detachment fault zone, but grade down-dip into a zone of crystal-plastic deformation dominated by mylonites (Reynolds and Lister, 1987).

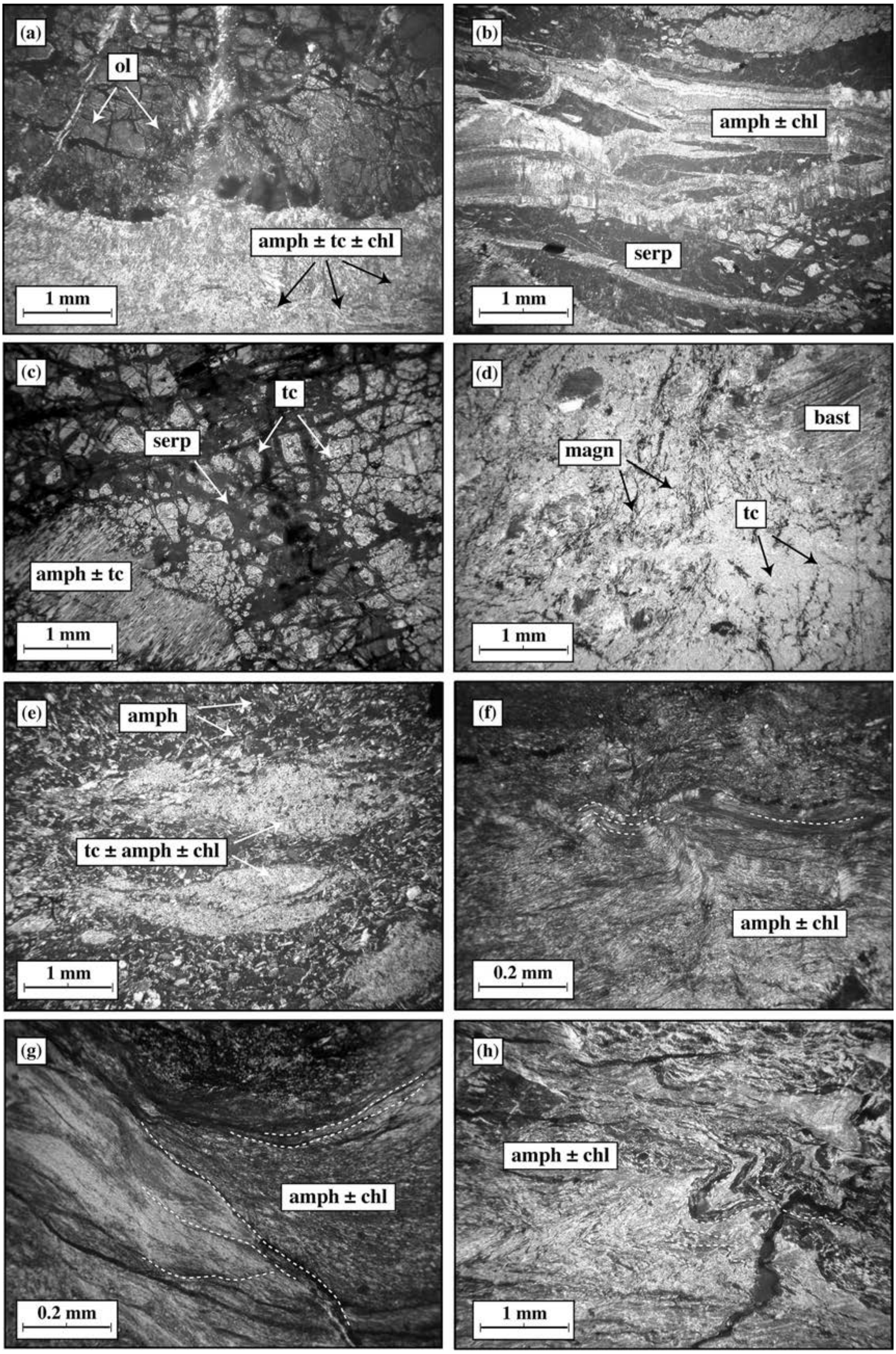

Fig. 4 - Representative photomicrographs of thin sections of the talc and amphibole-rich fault rocks from the Atlantis Massif (30°N; MAR), showing characteristic mineral assemblages, fabrics and microstructures. (a) Amphibole- and talc-rich band crosscutting a previously partially serpentinized peridotite (sample 3639-1256); (b) Incipient tremolite ± chlorite replacement and vein infill of a serpentinized peridotite (sample 3646-1000); (c) Incipient and static talc replacement of a serpentinized peridotite. Orthopyroxene is altered to amphibole ± talc ± chlorite (sample 3876-1310); (d) Serpentinite statically replaced by talc. Orthopyroxene porphyroclasts (altered to bastite) remain recognizable as well as magnetite trails (sample 3642-1308); (e) Amphibole schist showing amphibole-rich matrix surrounding elongate talc-rich ribbons (sample 3873-1250); (f), (g) and (h) Examples of amphibole schist showing the typical heterogeneous mylonitic texture with fine-grained bands of dynamically crystallized amphibole ± chlorite ((f) and (g) sample 3863-1419; (h) sample 3863-1425).

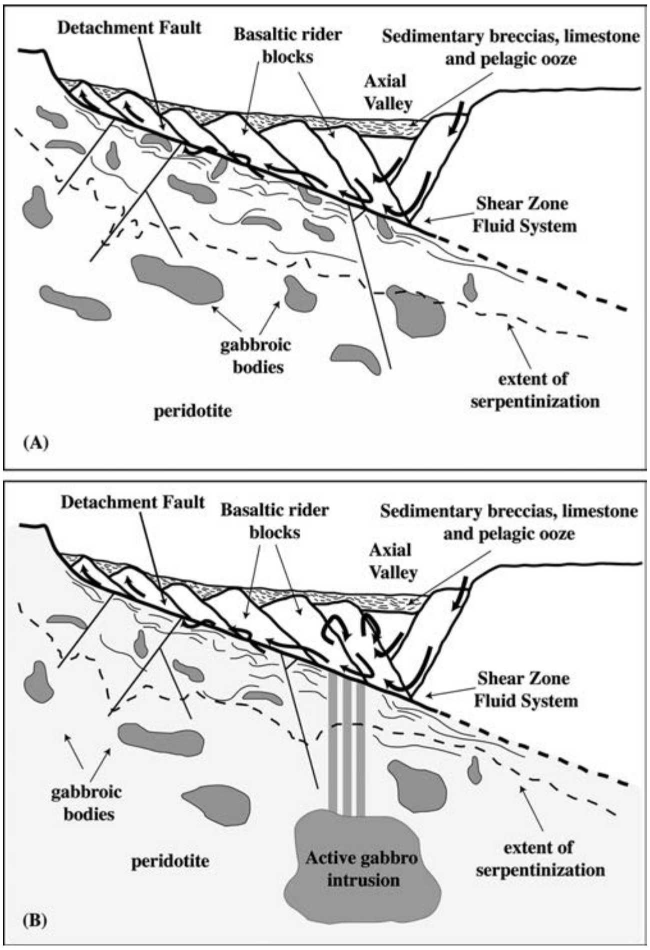

Fig. 5 - Schematic cross section showing fluid pathways and metasomatic zones related to an oceanic detachment zone (after Reynolds and Lister, 1997). (A) Interpretative model showing hydrothermal circulation of seawater-dominated fluids within gabbroic and serpentinitic rocks (following Bach et al., 2004 and Boschi et al., 2006a). (B) Interpretative model showing hydrothermal circulation of basalt-modified seawater fluids within serpentinites (following Escartín et al., 2003). In this model, detachment faulting was coeval with dyke intrusions across the fault, as indicated by the presence of both diabase intrusions into the fault zone and highly deformed diabases within the fault schists (Escartín et al., 2003).

An exception to this model is the case of the MAR 15°45'N OCC, where high-temperature metamorphism and deformation of the footwall is minimal and detachment faulting is believed to be localized along deformation zones in relatively cold serpentinized mantle peridotites (MacLeod et al., 2002; Escartín et al., 2003). This difference could reflect the fact that detachment faults can have different strain rates and can cut and expose different structural levels of the oceanic lithosphere during the long-lived evolution of an OCC (Escartín et al., 2003).

Most studies of deformation textures registered on the rocks sampled along the detachment surface reveal that strain may be localized in detachment faults over a wide range of temperature, in agreement with an evolving-shear-zone model across the brittle-plastic transition. Deformed serpentinites and gabbros at the Atlantis Bank SWIR (Cannat, 1991; Miranda E.A. et al., 2002), at the MARK area and Kane Megamullion core complex (Agar and Lloyd, 1997; Cannat et al., 1997; Cheadle et al., 2005)), at the Atlantis Massif (Schroeder and John, 2004; Boschi et al., 2006a), and at the Godzilla Mullion (Philippine Sea; Harigane et al. 2005) indicate strain localization at amphibolite grade (preferentially localized in gabbroic rocks) over a wide zone (up to 500 m), extensively overprinted by a narrow (~100-200 m) zone of low-temperature greenschist facies deformation (preferentially partitioned into altered or serpentinized peridotites) with formation of talc and amphibole-rich fault rocks. In contrast, studies of MacLeod et al. (2002) and Escartín et al. (2003) indicate strain localization in peridotite at greenschist- and subgreenschist-grade conditions with little evidence for precursor high-temperature deformation.

In summary, talc-amphibole fault rocks document the late exhumation stages of the mantle on the seafloor and mark the narrow zones of oceanic detachment faulting. This focused shear zone channels seawater-dominated derived fluids within lithologically heterogeneous sections of the lithosphere and promotes mass transfer and intense metasomatism.

In effect, the development of a detachment fault requires effective localization of deformation over long periods of time, resulting in enhanced hydrothermal fluid migration within the permeable, porous, and anisotropic fault zone and possibly lead to elevated fluid pressures (Escartín et al., 2003). Large gradients in fluid pressure and permeability may result, leading to continued, focused fluid flow. Reynolds and Lister (1987) suggested that focusing of fluid flow along relatively narrow, structurally weakened domains explains why syn-mylonitic retrogression is more pervasive in zones of high shear strain than in the less deformed wall rocks, even though all lower-plate rocks undergo the same drop in pressure and temperature as they are uplifted. Accordingly, outcrop relationships integrated with petrography and geochemistry (Escartín et al., 2003; Boschi et al., 2006a; Karson et al., 2006) show a dominance of undeformed over deformed rocks in the footwall of OCCs, reflecting the fact that high-strain deformation is highly localized along the detachment shear zone, leaving a large portion of the exposed lithosphere undeformed.

Deformation associated with the talc-amphibole assemblages under greenschist-facies conditions is highly heterogeneous and is marked by crystal-plastic (talc- and/or amphibole-schist) to cataclastic (talc-amphibole fels) behavior. Crystal-plastic deformation is likely focused in the narrow limited band of rocks along the detachment surface and results in distinctive strongly foliated talc and/or amphibole schists (Escartín et al., 2003; Schroeder and John, 2004; Boschi et al., 2006a). These rocks typically show a heterogeneous mylonitic texture (following Passchier and Trouw, 1998) characterized by a well-developed foliation composed of alternating layers of variably-sized, synkinematic talc, Ca-amphibole and chlorite and lenses, defined as ribbons (following Passchier and Trouw, 1998), in which strongly deformed and altered orthopyroxene porphyroclasts are embedded (Boschi et al., 2006a; Figs 3 and 4).

Cataclastic deformation at local scale (sample scale or smaller) has been observed by Escartín et al. (2003) and Schroeder and John (2004) in the form of bands of cataclastic porphyroclasts (mainly amphibole) in a fine matrix of syntectonically-grown minerals (amphibole ± chlorite ± talc ± serpentine), suggesting a complex history of ductile and cataclastic deformation with both reworking of fault rock and syntectonic growth of talc and amphibole.

Boschi et al. (2006a) observed that cataclastic deformation mainly affected the surrounding areas of the detachment zone at the Atlantis Massif and is characterized by the presence of talc or/and amphibole fels that lack a penetrative, high-strain deformation fabric but may show brittle deformation features, commonly in the form of fractures and veins. These rocks are dominated by static crystallization of fine-grained talc, Ca-amphibole ± chlorite, which variably replaces the precursor mineral phases (e.g. Fig. 4d). These observations suggest that a complementary product of hydrothermal circulation and focused fluid flow along the narrow detachment shear zone is a more pervasive, predominantly static metasomatism that affects a larger portion of the wallrocks.

On the other hand, the large variability in modes of deformation at small scale observed by Escartín et al. (2003) and Schroeder and John (2004) may indicate variations in pore fluid pressure (hydrofracturing) or be due to different deformation regimes during amphibole and talc formation. The fabric of the mylonites is strongly dependent on the lithotype and on the original structure of the rock in which it develops (Passchier and Trouw, 1998). The effect of low metamorphic grade on mylonitization of a bimineralic rock with one mineral that is "hard" (for example, amphibole) and one mineral that is "soft" (for example, talc) could be well represented by the fault rocks described by Escartín et al. (2003) and Schroeder and John (2004) where ductile deformed grains of the "soft" minerals wrap around fragmented, angular porphyroclasts of the harder mineral defining a well developed foliation and lineation. At medium grade conditions, both of the mechanically distinct mineral phases deform by crystal-plastic processes, but minerals such as amphibole are still stronger than talc and the foliation can contain fragments of partly recrystallized porphyroclasts (Passchier and Trouw, 1998).

CONCLUDING REMARKS

The development of talc- and amphibole-rich fault rocks within an ultramafic complex can occur in two distinct tectonic environments: (1) within the oceanic ridge system, along detachment faults and (2) as part of regional metamorphism of ophiolite complexes and orogenic ultramafic belts.

In the oceanic ridge setting, metasomatic talc- and amphibole-rich fault rocks commonly mark and weak the detachment zone, facilitate a prolonged slip and provide useful information about deformation and the P-T conditions during exhumation. Talc-amphibole-chlorite-mineral assemblages and microstructures in fault rocks indicate multiple stages of fluid infiltration and high strain-deformation in limited and discrete domains (Fig. 5). Heterogeneous (crystal-plastic to cataclastic) deformation observed at a small scale in talc and/or amphibole fault schists is in agreement with mylonitization of a bimineralic rock under greenschist-facies conditions. Surrounding areas could be affected by fracturing and pervasive static metasomatism under similar metasomatic condition. Available petrological and geochemical data show that bulk rock and hydrothermal fluid compositions are commonly controlled by the chemical compositions of mafic/ultramafic protoliths in a lithologically variable section of the oceanic lithosphere and are independent of the degree of deformation. Models of hydrothermal alteration and deformation (Bach et al., 2004; Escartín et al., 2003; Boschi et al., 2006a) propose intense and localized fluid circulation, focused along narrow shear (detachment) zones, affecting a heterogeneous lithosphere where gabbroic (or basaltic) rocks are inter-dispersed with serpentinized peridotites (Fig. 5). In such areas, seawater-dominated derived fluids are locally modified by interaction with gabbroic (basaltic) rocks to produce oxidizing, Si-Al-Ca-rich fluids at relatively low temperatures (≤ 500 °C).

The presence along fault zone of weak talc, one of the weakest minerals, can significantly reduce the overall rock strength (e.g., Edmond and Paterson, 1971; Escartín et al., 2004; 2005) and together with as well as other hydrous minerals (serpentine and chlorite) is of crucial importance for deformation mechanisms in such tectonic settings. These minerals may contribute to softening and lubricate mylonitic fault zones, facilitate dislocation along the detachment and lower its shear strength, concentrate movement along the faults, and allow these faults to remain active as " detachment faults". MacLeod et al. (2002; 2005) suggested that strain localization along the fault plane near the Fifteen-Twenty Fracture Zone of the MAR was highly effective and long lived, almost certainly as a result of the presence of very weak minerals such as serpentine, talc, and other hydrous silicates (e.g., chlorite, tremolite).

In addition, thin layers of deformed weak rocks could potentially represent a decollement zone and thus be reactivated in subduction zones or during the formation of orogenic ultramafic belts. The rheology of altered oceanic lithosphere, and its evolution during dehydration reactions plays an important role in subduction-zone processes (Escartín et al., 2005). The interpretation of thermal models for subduction zones depends on good constraints for both the strength of the down-going slab and the slab-wedge interface. Both of these physical properties may be controlled by the rheology of alteration products of peridotite, such as serpentine and talc.

The understanding of deformational and metasomatic processes occurring along the detachment faults could be greatly improved by the study of analogue structures preserved in ophiolitic units in orogenic belts.

Ophiolite studies to date report few occurrences of these peculiar fault rocks that can be surely ascribed to the detachment activity at spreading ridge. In the Northern Apennine, several ultramafic-hosted talc ore bodies have been mined in the past century but detailed, modern scientific studies are lacking. Moreover, the occurrence of talc- and amphibole-rich clasts inside Levanto Breccia was described by Cortesogno et al. (1981) but its important implication on the oceanic deformation-metasomatic history of the ophiolitic units was underestimated or ignored. Thus, the study of talc- and amphibole-rich fault rocks from non-metamorphosed ophiolites could shed new light on the tectonic evolution of amagmatic segments of ancient and modern slow spreading ridges.

The integration of studies of ophiolites, therefore, offer the marine community the benefits of a vast body of knowledge with regard to deeper structure and crustal compositions, which is unattainable in the deep sea. In turn, many of the regional structures that have recently been identified in active mid-ocean spreading systems now form a significant contribution to studies of ophiolite complexes. The complementary work of the two schools is clear and ripe for future development.

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