THE GENERATION OF LOWER OCEANIC CRUST IN (ULTRA-) SLOW SPREADING SETTINGS: INSIGHTS FROM THE ALPINE OPHIOLITES AND FROM THE GODZILLA MEGAMULLION (PARECE VELA BASIN)

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INTRODUCTION

Drill perforations and remote sensing showed that the oceanic crust at (ultra-)slow spreading ridges is frequently characterized by km-scale gabbroic bodies intruded into peridotites of mantle origin (*e.g.*, Cannat *et al.*, 1997; Kelemen *et al.*, 2004). Petrological and geochemical studies on these gabbroic sections revealed gabbroic lithologies with fairly different compositions (*e.g.*, Dick *et al.*, 2000; Blackman *et al.*, 2006) testifying the high compositional variability of the lower oceanic crust at (ultra-)slow spreading ridges (see also Dick *et al.*, 2010). The complex structure of the oceanic lithosphere, agrees several authors to the hypothesis that gabbros may have been formed from episodic melt intrusions variably intruded into the lithospheric oceanic mantle (*e.g.*, Cannat *et al.*, 1997). This process matches the sill-accretion models (Kelemen *et al.*, 1997), which is based on observations of the Oman ophiolite and is considered to be relevant for the formation of modern fast spreading ridges. However, the models of the creation of oceanic lithosphere at fast-spreading ridges are not appropriate for (ultra-)slow spreading ridges (*e.g.*, Dick *et al.*, 2000) and the processes constraining the formation of km-scale gabbroic sections in a scenario with relatively low melt supply are still controversial.

This thesis is aimed to constrain the processes that control the formation of the lower oceanic crust in context of low melt supply. In particular, we focused our research on the first phases of the lower crust generation process investigating the relationships between the lithospheric mantle and the primitive product of the crystallization of the basaltic melts rising from the asthenosphere. In this study we describe the formation and evolution of the lower oceanic crust from two different (ultra-)slow spreading settings, the Alpine ophiolites and the Parece Vela Basin (Philippine Sea).

GEOLOGICAL SETTING

The alpine ophiolites

The ophiolite bodies of the Alpine-Apennine system are lithospheric remnants of the Ligure-Piedmontaise (or western Tethys) basin. This basin developed in the Middle to Upper Jurassic in conjunction with the opening of the Central Atlantic Ocean, separating the Europe-Iberia plate to the northwest from the Africa-Adria plate to the southeast. Many authors advanced the hypothesis that most of the ophiolites from Alpine-Apennines system may be considered analogues of an ocean-continent transition developed in a magma poor system (*e.g.*, Marroni *et al.*, 1998). Anyway, several studies showed that a few ophiolitic sequences, considered to represent oceanward palaeo-geographic domains of the Jurassic Ligure-Piedmontaise basin, originally formed far from the continent. These successions are essentially represented by the Chenaillet ophiolite from Western Alps (*e.g.*, Lagabrielle & Cannat, 1990), the Mt. Maggiore mantle section from Corsica (Rampone *et al.*, 2008) and the Internal Ligurian ophiolites from Northern Apennine (Tribuzio *et al.*, 2004; Principi *et al.*, 2004) (Fig. 1). Although, the origin of the mantle rocks associated with these gabbros is still matter of debate (Piccardo *et al.*, 2007; Rampone *et al.*, 2008) there is a general consensus that the gabbros from the innermost domains of the Ligure-Piedmontaise basin share many lithostratigraphic, structural and compositional features with modern gabbroic section from (ultra-)slow spreading ridges. These gabbros may thus be considered relevant to obtain models of accretion and exhumation of oceanic crust at (ultra-)slow-spreading ridges.

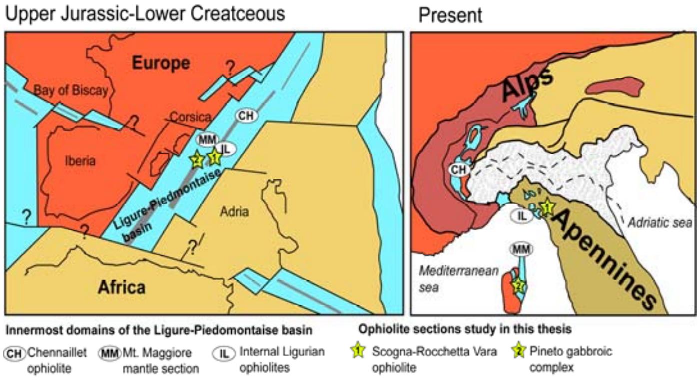

Fig. 1 - Paleogeographic and present-day tectonic maps of the Alpine-Apennines system and position of the studied ophiolite sections.

The Godzilla Megamullion (Parece Vela Basin)

Godzilla Megamullion is an extremely large megamullion, which extends for 55 km along and 125 km perpendicular to the axis of the central Parece Vela Basin (Philippine Sea). This basin is an extinct backarc basin located between the Kyushu-Palau Ridge and the West Mariana Ridge (Fig. 2). The Godzilla Megamullion is exposed on the southwestern flank of segment S1. Similar to the oceanic core complexes exposed along (ultra-) slow spreading ridges, the Godzilla Megamullion is characterized by topographic corrugations which extend parallel to the spreading direction from the axial valley of the ridge towards the breakaway area. The Godzilla Megamullion has large lateral heterogeneity in the crust, varying from regions dominated by mantle peridotite, overlain by a carapace of diabase and basalt, to regions with a massive gabbroic section (*e.g.*, Ohara & Snow, 2009). The samples studied in this thesis were collected during the dive 6K-1147 located ~ 15 km from the breakaway area of the Godzilla Megamullion. This area is considered to represent the zone where the detachment fault initially nucleated and in is clearly marked by linear and low-relief abyssal hills parallel the strike of the spreading axis at the south-west edge of the complex. The studied samples consist of troctolites and olivine-gabbros.

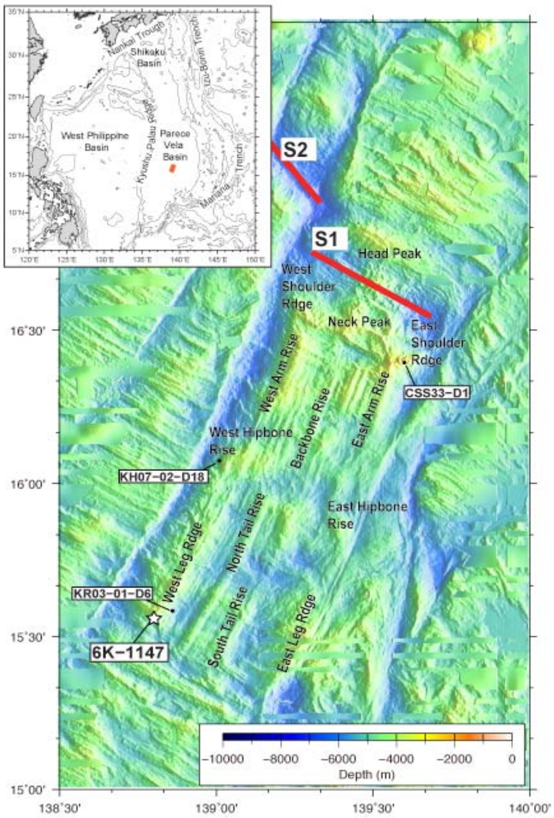

Fig. 2 - The inset map shows the major bathymetric features of the Western Pacific (after Ohara *et al.*, 2003). The red square shows the location of the Godzilla Megamullion into the Parece Vela Basin. The main map is a bathymetry map of the Godzilla Megamullion showing the locations of dredge sites and dives that recovered the gabbroic rocks studied so far (Ohara *et al.*, 2003; Harrigane *et al.*, 2008). The location of dive 1147 is shown by the white star. The inactive spreading segments S1 and S2 are marked by thick red lines. The names of the topographic features in the Godzilla Megamullion are also shown.

THE MANTLE EVOLUTION IN THE INNERMOST DOMAINS OF THE JURASSIC LIGURE-PIEDMONTAISE BASIN (INTERNAL LIGURIAN OPHIOLITES)

The Mantle Sequence Scogna-Rocchetta Vara Ophiolite

The studied ophiolite is exposed for ~ 15 km^2 and consists mainly of two tectonic successions, namely the Scogna and Rocchetta Vara. The Scogna succession consists mostly of an altered gabbroic section that is locally overlain by gabbroic breccias. The Rocchetta Vara succession is characterised by a gabbro-peridotite basement overlain by a sedimentary cover made up of gabbroic breccias, Middle-Upper Jurassic radiolarian cherts and Cretaceous shaly pelagites (Principi *et al*., 2004). The Rocchetta Vara mantle sequence mostly consists of peridotites commonly showing extensive serpentinization. The original fabric is generally preserved and the peridotites show porphyroclastic to tectonitic foliation, characterised by alignment of porphyroclastic orthopyroxene and spinel. The peridotites locally include up to 3 cm thick pyroxene-rich layers that are generally boudinaged and elongated nearly concordantly with respect to the foliation of the host rocks. The peridotites frequently contain subparallel plagioclase-rich veinlets (up to 2 mm thick and up to 2 cm long) that broadly follow the foliation of the host rocks.

The Rocchetta Vara mantle sequence locally also includes dunite bodies that are up to metre-scale in thickness. These bodies are elongated nearly parallel to the tectonitic foliation and include mm-scale aggregates made up of euhedral spinel. The peridotite foliation and the dunite bodies are locally crosscut by troctolite to olivine-gabbro dikes. These dikes are up to metre-scale in thickness and commonly show diffuse contacts with the host rocks. In one sector of the Rocchetta Vara succession, a gabbroic intrusion (up to 400 m thick) is exposed below a ~ 150 m thick mantle sequence. In particular, the mantle sequence overlying the gabbroic intrusion contains sills up to 3 m thick. These gabbroic sills display sharp planar boundaries to the host peridotites, without grain size reduction and commonly crosscutting the gabbro dike at a high angle (~ 70°).

Hot Lithospheric Evolution of the Mantle Sequence

The mantle sequence of Scogna-Rocchetta Vara shows a composite melt-transport and deformation history, which deals with its evolution from the spinel-plagioclase mantle condition, to the intrusion of discrete gabbroic bodies (Fig. 3). In this work we suggest that the spinel-facies mantle precursor of the Scogna-Rocchetta Vara ophiolite were moderately depleted peridotites. This geochemical signature indicates that these rocks could represent *i*) residues after a low degree partial melting of an asthenospheric source (see also Rampone *et al.*, 1996) or *ii*) product of interaction of a lithospheric peridotite protoliths with highly depleted, olivine-saturated melts derived from the underlying asthenosphere (Rampone *et al.*, 2008). The plagioclase requilibration and the successive serpentinization of these rocks prevent a detailed geochemical characterization and we cannot discriminate between these two different origins by the chemistry of the rock. However, our study shows that all the event of melt-rock interaction and deformation suffered by the studied mantle are compatible with those

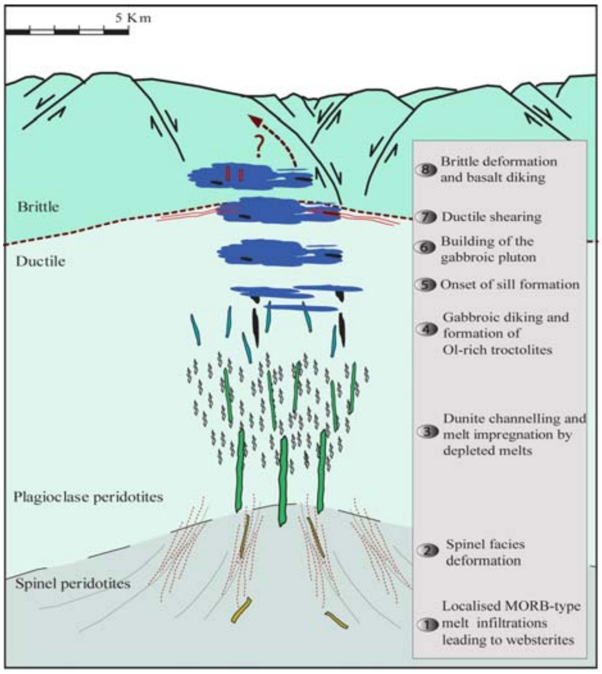

Fig. 3 - Conceptual model for the tectono-magmatic evolution of Scogna-Rocchetta Vara ophiolite. Websterites, dunites, gabbroic dikes and sills are exaggerated in scale. The transition between spinel and plagioclase peridotite is assumed to be 0.7 GPa.

described in some modern (ultra-)slow spreading center. We recognized a series of melt/peridotite interaction events, either diffuse or channeled, which modified the composition of the precursor mantle. Localized infiltrations of MORB-type melts gave rise to formation of spinel websterite layers close to the lithosphere-asthenosphere boundary. The peridotite-websterite association was involved in a spinel facies deformation attributed to emplacement of asthenospheric material at the base of the lithosphere. The successive exhumation of the mantle section from spinel to plagioclase facies conditions was accompanied by the injection of depleted melt leading to the formation of replacive dunites and plagioclase impregnation. These events constitute the "hot" lithospheric evolution of the mantle sequence. The cooling of the mantle sequence leads to the crystallization of gabbroic material within the mantle and the formation of the km-scale gabbroic plutons.

THE FORMATION OF A KM-SCALE LOWER CRUSTAL SEQUENCE FROM CORSICA OPHIOLITES (PINETO GABBROIC SEQUENCE)

The Large Scale Structure of the Pineto Gabbroic Sequence

The Pineto gabbroic sequence outcrops in Northern Corsica; the sequence is situated at the top of the Alpine tectonic stack and is unaffected by the Alpine-related metamorphic re-crystallization under high pressure/low temperature conditions. It mostly consists of layered troctolites, olivine-gabbros and clinopyroxene-rich gabbros, whose whole-rock compositions indicate a process of fractional crystallization from MORB-type melts (Beccaluva *et al.*, 1977; Saccani *et al.*, 2000). The gabbroic sequence is covered to NW by a meter scale thick MORB-type basalt flow, in turn followed by a sedimentary cover consisting of Middle-Upper Jurassic radiolarian cherts and Lower Cretaceous shaly pelagites (Durand-Delga *et al.*, 2005).

The Pineto gabbroic sequence may be subdivided into two main portions displaying different bulk compositions: the upper portion of the sequence, toward the sedimentary cover, mainly consists of clinopyroxene-rich gabbros locally interlayered with troctolite lenses containing olivine-rich (Ol ~ 80 vol%) troctolite bodies. The stratigraphically lower portion is mostly made up of troctolites and Ol-gabbros. The modal/grain-size layering is concordantly NW-deeping throughout the Pineto gabbroic sequence, thereby allowing us to evaluate its thickness in ~ 2 km. Notably, the estimated thickness exceeds the maximum depth reached by drill perforations at (ultra-)slow spreading ridges (Dick *et al.*, 2000; Blackman *et al.*, 2006). Several bodies of serpentinized mantle peridotites (up to 100 m in thickness) were also found within the gabbroic sequence. The Hole U1309D at Mid Atlantic Ridge (Blackman *et al.*, 2006) drilled rock types those are structurally and compositionally similar to those constituting the Pineto gabbroic sequence. For instance, olivine-rich troctolite bodies and slices of serpentinized peridotites of mantle origin were collected in both Hole U1309D (see also Suhr *et al.*, 2008) and Pineto gabbroic sequence. The large-scale structure of the Pineto gabbroic sequence is mainly distinct from Hole U1309D in the high proportion of troctolites in its lowermost sector.

Model for the growth of the lower crustal sequence

Petrological variations of mineral cores (plagioclase olivine and clinopyroxene) and cooling rate estimates using Ca in olivine geospeedometer (see Coogan *et al.*, 2005) document that the complex architecture of the studied gabbroic sequence is produced by the association of variably evolved sill-shaped intrusions that were derived from the different primitive melt injections, similar to the sill accretion model proposed for the gabbroic pluton exposed at (ultra-)slow spreading ridges (*e.g.*, Grimes *et al.*, 2008).

For the sake of simplicity, it deals with the building of a gabbroic sequence formed by two different primitive melt injections. In the first stage, the gabbroic sequence started to grow through the sill accretion model proposed by Kelemen *et al.* (1997) for the Oman ophiolite. A primitive melt is intruded within a lithospheric mantle that is cooled by active hydrothermal circulation and crystallizes *in situ*, thereby forming sills consisting of primitive troctolites. The melts residual after the formation of the troctolites migrate through focused flow and develop sills that are progressively more evolved upward. In the second stage, a new primitive melt injection involves the lithospheric section. This primitive melt may intrude the lithospheric mantle below the first stage primitive troctolites, thereby forming primitive troctolites at deeper levels. Alternatively, the new primitive melt injection dissects the sills derived from the first primitive melt injection and develop primitive troctolites at shallower levels. In both cases, the melts, residual after the formation of the second stage primitive troctolites, migrate upward and yield a series of variably evolved sills intruding the first stage sill series. Evolved gabbroic sills derived from different primitive melt injections may therefore be physically associated.

If repeated injections of primitive mantle-derived melts occur, this process will lead to a km-scale gabbroic sequence characterized by: *i*) primitive troctolite lenses at different depths, and *ii*) a high proportion of primitive and evolved gabbroic rocks in its lower and upper portion, respectively. The increasing thickness of the cumulate pile may produce compaction of the lower sills, thereby enhancing the separation of the interstitial evolved melts and leading to minor diffuse melt flow. It is worth to note that the growth of the gabbroic section from Hole U1309D at Mid Atlantic Ridge was attributed to different episodes of sill intrusive activity on the basis of U/Pb zircon geochronology (Grimes *et al.*, 2008), thereby matching the proposed conceptual model for the Pineto gabbroic sequence.

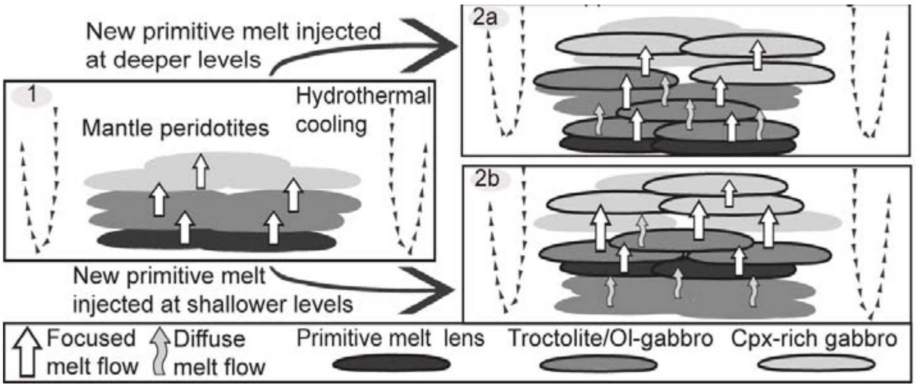

Fig. 4 - Sketch representing the proposed conceptual model for the growth of the Pineto gabbroic sequence. Sills lack or have black boundaries to represent sills derived from the first and the second mantle-derived batch, respectively.

MELT-PERIDOTITE INTERACTIONS DURING THE FIRST PHASES OF THE FORMATION OF THE GABBROIC PLUTONS: EVIDENCE FROM THE TROCTOLITES OF THE GODZILLA MEGAMULLION

Troctolites and olivine-gabbros from Godzilla Megamullion

Troctolites are subdivided into Ol- and Pl-troctolites (olivine or plagioclase > 60% respectively). Ol-troctolites are the most abundant variety, with high Fo, rounded polygonal olivine (up to 0.5-5 mm). Plagioclase is subhedral to rarely oikocrystic, whereas coarse-grained Cpx oikocrysts (up to 30 mm) are common and locally may reach up to 10 vol% (Fig. 3a). Cpx films, intergranular to olivine, are optically continuous with nearby Cpx oikocrysts. Commonly, Cpx shows planar crystal faces against the plagioclase and irregular embayed morphologies against olivine. Similar textures and compositions have been documented in other Ol-rich troctolites from U1309D at Mid Atlantic Ridge (*i.e.*, Drouin *et al.*, 2009; Suhr *et al.*, 2008) and from Alpine ophiolites (*i.e.*, Renna & Tribuzio, 2011). In particular, these authors interpreted these rocks as the products of partial dissolution and impregnation of a dunite matrix. The dunite having, itself, been formed by melt-rock reaction between MORB and mantle peridotite. In this study we show that a similar process can explain the texture and the composition of the Ol-troctolites from Godzilla Megamullion. However, the different composition of the olivine from Godzilla Megamullion Ol-troctolites reflects a different environment of formation. The Pl-troctolites have anhedral to oikocrystic olivine in a plagioclase matrix. Olivine oikocrysts occur in all sections, reaching 30 mm in size. Plagioclase chadacrysts are commonly present within olivine oikocrysts, where they frequently have rounded boundaries, subhedral habits and irregular shape. These textures indicate the local dissolution of the plagioclase during olivine crystallization. Note that the grain boundaries between olivine oikocrysts and plagioclase are always curved and that inverse zoning of the resorbed plagioclase chadacrysts within olivine indicates partial re-equilibration of the plagioclase with a more primitive exotic melt. Cpx in the Pl-troctolites varies from interstitial grains to coarse-grained oikocrysts. The Ol-gabbro has euhedral to subhedral plagioclase (0.5-7 mm), subhedral to interstitial olivine (0.5-2 mm) and granular to poikilitic Cpx. Note that high Mg# and Cr in Cpx oikocrysts from the Ol-troctolites, the Pl-troctolites and the Ol-gabbros indicate crystallization through dissolution of high Fo olivine (see also Lissenberg & Dick, 2008) rather that crystallization at high pressures (Elthon, 1987).

Melt-mantle interactions: modelling the formation of the Ol-rich troctolites and their influences on the composition of evolved gabbros

Located in a mantle outcrop 15-km from the breakaway zone of Godzilla Megamullion, the Dive 6K-1147 troctolites and olivine gabbros reflect sub-axial melt evolution in the shallow cold lithosphere of the ancient backarc Parece Vela Ridge. Their composition was controlled by melt-rock reaction with the enclosing mantle, reflecting solidification by reaction and conductive cooling of ascending melts. They are distinguished by lower olivine nickel contents from olivine-rich troctolites found enclosed in the thick gabbro sequence at Atlantis Massif (Drouin *et al.*, 2009; Suhr, 2008). Modelling the formation of these rocks in the forsterite *versus* NiO space, we found that the nickel content of olivine has strong importance in constraining the environment of formation of olivine-rich rocks in the lower crust and mantle, the extent and nature of the processes by which they form, and the magma budget involved.

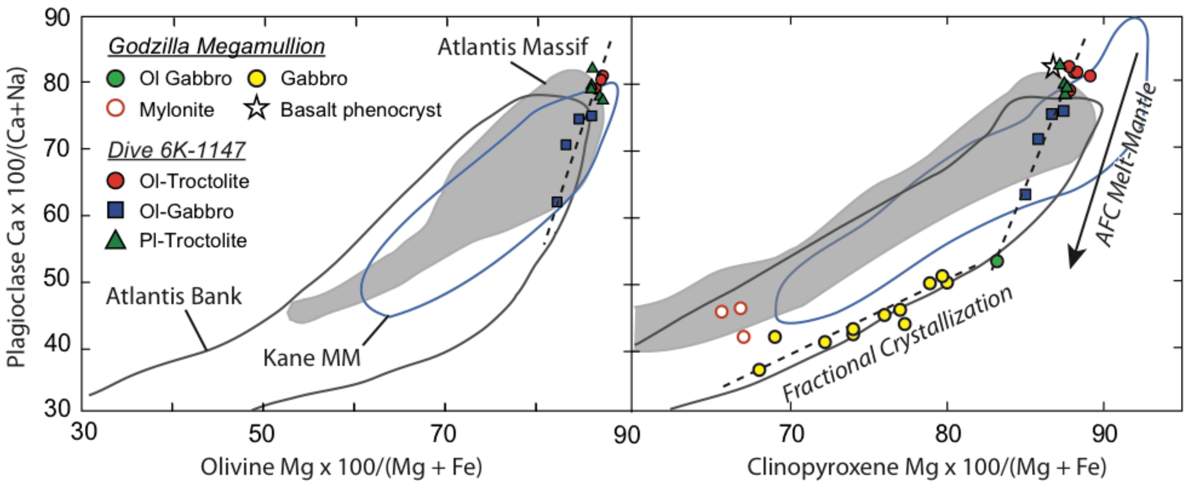

Fig. 5 - Variation of forsterite content in olivine and Mg# in Cpx *versus* anorthite content in plagioclase for mineral cores from the gabbros and troctolites of the Godzilla Megamullion (Ohara *et al.*, 2003; Harigane *et al.*, 2008; this study). Abyssal gabbros from Dick *et al*., 2002; Suhr *et al*., 2008; Lissenberg & Dick, 2008; Drouin *et al*., 2009; Dick *et al*., 2010.

Furthermore, these mantle-melt reaction processes produced differentiated melts that then followed a crystal-line of descent parallel (but at lower An) to that found for large abyssal gabbro massifs, such as Atlantis Bank and Atlantis Massif, where the influence of the mantle on evolving liquids was minimal, and melts generally more closely follow a simple fractional crystallization trend (Fig. 5). Troctolites similar to those reported here were recovered in gabbroic segregations drilled in dunite crosscutting residual harzburgite at Hess Deep (East Pacific Rise) mantle (see Fig. 12f in Dick & Natland, 1996). Trace element analyses of Cpx in these channels documented for the first time that fully aggregated MORB forms in the mantle prior to intrusion to crustal levels (Dick & Natland, 1996), consistent with our interpretation of the Godzilla troctolites. It is noteworthy that our data, along with that from Hess Deep, show that melt stagnation and mantle-melt reactions are present across the range of the ocean ridge spreading rate spectrum.

GENERAL CONCLUSIONS

In this study we emphasized the similarities between two sections of the Ligurian and Corsica ophiolites and some abyssal section from (ultra-)slow spreading ridges. We thus propose a model for the generation of the oceanic lithosphere of the Ligure-Piedmontaise basin, which resembles the models of proposed for the slow-spreading ridges. In the mantle sequence of Scogna-Rocchetta Vara ophiolite, we recognized a series of melt/peridotite interaction events, either diffuse or channelled, which modified the composition of the precursor mantle. Localized infiltrations of MORB-type melts at high pressures forming spinel websterite layers; a spinel facies deformation attributed to emplacement of asthenospheric material at the base of the lithosphere; the exhumation of the mantle section from spinel to plagioclase facies conditions was accompanied by the formation of replacive dunites and plagioclase impregnation. This constitutes the “hot” lithospheric evolution of the mantle sequence. The cooling of the mantle sequence leads to the crystallization of gabbroic material within the mantle and the formation of the km-scale gabbroic plutons. In particular, the study of the Pineto gabbroic sequence allowed us to obtain a model for the formation of the lower crust through a process of accretion of sill-shaped intrusions derived from different primitive melt injections.

Then, we focused our research on the first phases of the formation of the pluton studying the primitive crystallization products of the melt rising from the mantle, studying the troctolites and associated gabbros from the breakaway area of the Godzilla Megamullion (Parece Vela Basin, Philippine Sea). We showed that the melt-rock interaction widely occur within the mantle lithosphere forming hybrid rocks containing high amount of mantle material. Modelling the formation of these rocks we inferred that the mantle-melt reaction processes may affect the chemistry of the entire lower oceanic crust.

REFERENCES

Beccaluva, L., Ohnenstetter, D., Ohnenstetter, M., Venturelli, G. (1977): The trace element geochemistry of corsican ophiolites. *Contrib. Mineral. Petrol*., **64**, 11-31.

Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the Expedition 304/305 Scientists (2006): Ocean core complex formation, Atlantis Massif. *Proc. IODP*, **304-305**, doi:10.2204/iodp.proc.304305.2006.

Cannat, M., Chatin, F., Whitechurch, H., Ceuleneer, G. (1997): Gabbroic rocks trapped in the upper mantle at the Mid-Atlantic Ridge. *Proc. ODP, Sci. Results,* **153**, 243-264.

Coogan, L.A., Hain, A., Stahl, S., Chakraborty, S. (2005): Experimental determination of the diffusion coefficient for calcium in olivine between 900 degrees C and 1500 degrees C. *Geochim. Cosmochim. Acta,* **69,** 3683-3694.

Dick, H.J.B. & Natland, J.H. (1996): Late stage melt evolution and transport in the shallow mantle beneath the East Pacific Rise. *Proc. ODP, Sci. Results*, **147,** 103-134.

Dick, H.J.B., Natland, J.H., Alt, J.C., Bach, W., Bideau, D., Gee, J.S., Haggas, S., Hertogen, J.G.H., Hirth, G., Holm, P.M., Ildefonse, B., Iturrino, G.J., John, B.E., Kelley, D.S., Kikawa, E., Kingdon, A., LeRoux, P.J., Maeda, J., Meyer, P.S., Miller, D.J., Naslund, H.R., Niu, Y.L., Robinson, P.T., Snow, J., Stephen, R.A., Trimby, P.W., Worm, H.U., Yoshinobu, A. (2000): A long in situ section of the lower ocean crust: results of ODP Leg 176 drilling at the Southwest Indian Ridge. *Earth Planet. Sci. Lett.*, **179**, 31-51.

Dick, H.J.B., Ozawa, K., Meyer, P.S., Niu, Y., Robinson, P.T., Constantin, M., Hebert, R., Maeda, J., Natland, J.H., Hirth, G., Mackie, S. (2002): Primary silicate mineral chemistry of a 1.5- km section of very slow spreading lower ocean crust: ODP Hole 735B, Southwest Indian Ridge**.** *Proc. ODP, Sci. Results,* **176**, 1-60.

Dick, H.J.B., Lissemberg, C.J., Warren, J.M. (2010): Mantle Melting, Melt Transport, and Delivery Beneath a Slow-Spreading Ridge: The Paleo-MAR from 23°15’N to 23°45’N. *J. Petrol.*, **51**, 425-467.

Drouin, M., Godard, M., Ildefonse, B., Bruguier, O., Garrido, C.J. (2009): Geochemical and petrographic evidence for magmatic impregnation in the oceanic lithosphere at Atlantis Massif, Mid-Atlantic Ridge (IODP Hole U1309D, 30°N). *Chem. Geol.*, **264**, 71-88.

Durand-Delga, M., Fondecave-Wallez, M.J., Rossi, P. (2005): L’unité ophiolitique de Pineto (Corse): signification du détritisme continental dans sa couverture de flysch albo-cénomanien. *C.R. Geosci.*, **337**, 1084-1095.

Elthon, D. (1987): Petrology of gabbroic rocks from the Mid-Cayman Rise spreading center, *J. Geophys. Res.*, **92**, 658-682.

Grimes, C.B., John, B.E., Cheadle, M.J. (2008): Protracted construction of gabbroic crust at a slow spreading ridge: Constraints from $^{206}Pb/^{238}U$ zircon ages from Atlantis Massif and IODP Hole U1309D (30°N, MAR). *Geochem. Geophys. Geosyst.*, **9**, doi:10.1029/2008GC002063.

Harigane, Y., Michibayashi, K., Ohara, Y. (2008): Shearing within lower crust during progressive retrogression: structural analysis of gabbroic rocks from the Godzilla Megamullion, an oceanic core complex in the Parece Vela backarc basin. *Tectonophysics*, **457**, 183-196, doi:10.1016/j.tecto.2008.06.009.

Kelemen, P.B., Hirth, G., Shimizu, N., Speigelman, M., Dick, H. (1997): A review of melt migration processes in the adiabatically upwelling mantle beneath oceanic spreading ridges. *Phil. Trans. Roy. Soc. London*, **A355**, 283-318.

Kelemen, P.B., Kikawa, E., Miller, D.J. (eds.) (2004): Proceedings of the Ocean Drilling Program, Part A: Initial Reports, **209**. Ocean Drilling Program College Station, TX.

Lagabrielle,Y. & Cannat, M. (1990): Alpine Jurassic ophiolites resemble the modern central Atlantic Basement. *Geology*, **18**, 319-322.

Lissenberg, C.J. & Dick, H.J.B. (2008): Melt-rock reaction in the lower oceanic crust and its implications for the genesis of mid-ocean ridge basalt. *Earth Planet. Sci. Lett.*, **271**, 311-325.

Marroni, M., Molli, G., Montanini, A., Tribuzio, R. (1998): The association of continental crust rocks with ophiolites in the northern Apennines (Italy): implications for the continent-ocean transition in the Western Tethys. *Tectonophysics*, **292**, 43-66.

Ohara, Y. & Snow, J.E. (2009): Godzilla Mullion: current understanding on the nature of the world's largest oceanic core complex. *Eos, Trans. Am. Geophys. Union*, **90**, abs. T33D-06.

Ohara, Y., Fujioka, K., Ishii, T., Yurimoto, H. (2003): Peridotites and gabbros from the Parece Vela backarc basin: unique tectonic window in an extinct backarc spreading ridge. *Geochem. Geophys. Geosyst.*, **4**, 1029, doi: 10.1029/2002GC000469.

Piccardo, G.B., Zanetti, A., Müntener, O. (2007): Melt/peridotite interaction in the Southern Lanzo peridotite: Field, textural and geochemical evidence. *Lithos*, **94**, 181-209.

Principi, G., Bortolotti, V., Chiari, M., Cortesogno, L., Gaggero, L., Marcucci, M., Saccani, E., Treves, B. (2004): The pre-orogenic volcano-sedimentary covers of the Western Tethys oceanic basin: a review. *Ofioliti*, **29**, 177-212.

Rampone, E., Hofmann, A.W., Piccardo, G.B., Vannucci, R. Bottazzi, P., Ottolini, L. (1996): Trace element and isotope geochemistry of depleted peridotites from an N-MORB type ophiolite (Internal Liguride, N. Italy). *Contrib. Mineral. Petrol.*, **123**, 61-76.

Rampone, E., Piccardo, G.B., Hofmann, A.W. (2008): Multi-stage melt-rock interaction in the Mt. Maggiore (Corsica, France): ophiolitic peridotites: microstructural and geochemical evidence. *Contrib. Mineral. Petrol.*, **156**, 453-475.

Renna, M.R & Tribuzio, R. (2011): Olivine-rich troctolites from Ligurian ophiolites (Italy): evidence for impregnation of replacive mantle conduits by MORB-type melts, *J. Petrol.*, **52**, 1763-1790.

Saccani, E., Padoa, E., Tassinari, R. (2000): Preliminary data on the Pineto gabbroic Massif and Nebbio basalts: progress toward the geochemical characterization of Alpine Corsica ophiolites. *Ofioliti*, **25**, 75-85.

Suhr, G., Hellebrand, E., Johnson, K., Brunelli, D. (2008): Stacked gabbro units and intervening mantle: A detailed look at a section of IODP Leg 305, Hole U1309D. *Geochem. Geophys. Geosyst.*, **9**, Q10007, doi:10.1029/2008GC002012.

Tribuzio, R., Thirwall, M.F., Vannucci, R. (2004): Origin of the gabbro-peridotite association from the Northern Apennine ophiolites (Italy). *J. Petrol*., **45**, 1109-2277.