GEOCHEMICAL AND Sr, Nd, Pb ISOTOPE INVESTIGATION OF THE NEW CALEDONIA OPHIOLITE

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INTRODUCTION

Ophiolites have attracted much scientific interest since their recognition as surface exposures of fossil oceanic lithosphere accreted to continental margins (Dilek & Furnes, 2011 and references therein).

The accessibility of ophiolitic sequences makes them an excellent natural laboratory for the study of oceanic lithosphere. Hence, field-based geochemical investigation of ophiolitic peridotites may prove valuable in understanding melt extraction and melt/rock interaction processes in the upper mantle. The genesis of oceanic lithosphere differs with geodynamic setting, *i.e.*, mid-ocean ridge (MOR), ocean-continent transition (OCT), and supra-subduction zone (SSZ), and has distinct structural and chemical properties that permit their identification (Miyashiro, 1973; Pearce *et al.*, 1984; Dilek & Furnes, 2011). Coexistence of peridotites with contrasting geochemical signatures indicative of MOR-type and SSZ-type melting regimes has been documented in other ophiolitic sequences (*e.g.*, Lycian and Antalya ophiolitic complexes from Turkey and Coast Range ophiolites; Aldanmaz *et al.*, 2009; Choi *et al.*, 2008). Geochemical and mineralogical characteristics of mantle residua may be an effective tool to identify the geodynamic setting of ophiolite formation.

In this work a comprehensive petrographic, geochemical and isotopic study of the peridotitic and mafic lithotypes belonging to the New Caledonia ophiolite has been performed. The research was carried out following a multidisciplinary approach including field work (sampling), petrography, determination of bulk rock and mineral composition (major and trace element), measurement of Sr, Nd, and Pb isotopic ratios, both for whole rock and minerals.

GEOLOGICAL AND PETROLOGICAL BACKGROUND

New Caledonia is located in the South West Pacific ocean. The island represents the northern extension of the Norfolk Ridge and is composed of a complex association of volcanic, sedimentary and metamorphic terranes ranging in age from Permian to Miocene (Cluzel *et al.*, 2001, 2012). In particular, New Caledonia can be subdivided into four main geological domains (Cluzel *et al.*, 2001): (i) the Basement units (pre-Late Cretaceous ba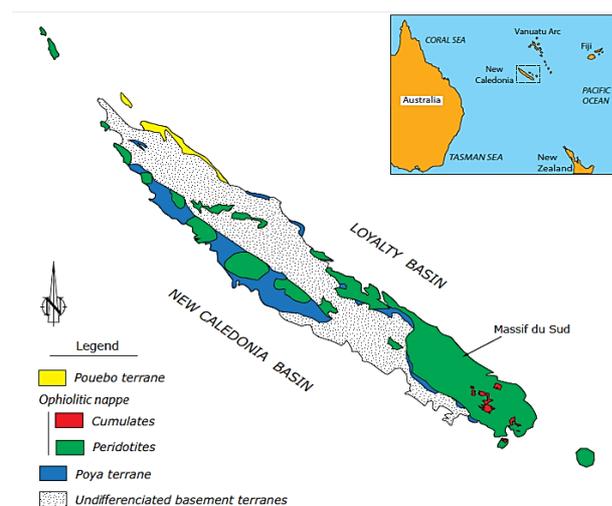sement and Late Coniacian-to-Late Eocene sedimentary cover), (ii) the Cenozoic high-pressure metamorphic belt, (iii) the basaltic Poya Terrane and (iv) a large slab of obducted peridotites, the Peridotite Nappe (see Fig. 1). The Peridotite nappe is an allochtonous sheet of oceanic lithosphere from the Loyalty Basin thrust from NNE to SSW over the continental basement of the island in the Late Eocene (Prinzhofer *et al.*, 1980). Its emplacement has been related to the failed subduction of the New Caledonia continental basement in a NE-dipping

Fig. 1 - Simplified geological map of the New Caledonia (modified after Ulrich *et al.*, 2010).

subduction zone, which culminated with the obduction of the Loyalty oceanic lithosphere (Cluzel *et al.*, 1998). The Peridotite Nappe overlies the basaltic Poya Terrane, separated by a sub-horizontal thrust fault and a thick (50-200 m) sole of serpentinite mylonites, locally associated with high-temperature amphibolite lenses formed during subduction initiation in the Early Eocene (Cluzel *et al.*, 2012).

The New Caledonia Peridotite Nappe is one of the largest ophiolite complexes in the world. The ophiolite is dominated by mantle lithologies (mainly refractory harzburgites, together with minor spinel and plagioclase lherzolites), locally capped by mafic-ultramafic cumulates. Although the New Caledonia mantle bodies have been the subject of several petrological and geochemical investigations starting from the 1980s (Prinzhofer *et al.*, 1980, Dupuy *et al.*, 1981; Nicolas & Dupuy, 1984; Prinzhofer & Allègre, 1985), the ultra-depleted nature of these rocks hampered their geochemical characterization. In particular, isotopic data for the peridotites are still lacking, save for some Pb isotope data (Hamelin *et al.*, 1984).

Over the past decade, several petrological and geochemical investigations were undertaken to understand the origin of the harzburgites and the associated mafic and ultramafic intrusive rocks (Marchesi *et al.*, 2009; Ulrich *et al.*, 2010; Pirard *et al.*, 2013). These studies converged on the consensus that the harzburgites are of a SSZ (supra subduction zone) affinity and that the overlying mafic-ultramafic sequence represent a crust-mantle section, formed in a nascent arc environment (Marchesi *et al.*, 2009; Pirard *et al.*, 2013). These geochemical studies also show that the dunites and the wehrlites belonging to the ultramafic sequence derive from melt/peridotite interaction processes involving primitive arc tholeiites and boninitic liquids, whereas the mafic rocks are the result of cumulus processes (Marchesi *et al.*, 2009; Pirard *et al.*, 2013).

The lherzolites are the less known lithotypes among the rocktypes belonging to the New Caledonia ophiolite. A relatively limited geochemical dataset is available for these lithotypes (Ulrich *et al.*, 2010) meaning that their evolution and geodynamic affinity are poorly understood. In particular, a debated issue concerns the existence of a genetic link between the New Caledonia lherzolites and the basaltic unit of Poya, which tectonically underlies the Peridotite Nappe (Eissen *et al.*, 1998; Marchesi *et al.*, 2009; Whattam, 2009).

RESULTS AND DISCUSSION

The New Caledonia peridotites are low-strain tectonites showing porphyroclastic textures, sometimes grading into promylonitic textures. The lherzolites display moderate serpentinisation degrees (LOI = 6.39-10.69 %), whereas the harzburgites are represented by extremely fresh rocktypes.

Spinel lherzolites are relatively undepleted, as attested by the presence of 7-8 vol.% of Na_2O and Al_2O_3-rich clinopyroxene (up to 0.5 wt.% Na_2O; 6.5 wt.% Al_2O_3), moderate Fo content of olivine (88.5-90.0 mol.%) and low Cr# of spinel ([100 * Cr/(Cr+Al)] = 13-17).

The harzburgites display a highly refractory character, as testified by the remarkable absence of primary clinopyroxene, very high Fo content of olivine (90.9-92.9 mol.%), high Mg# of orthopyroxene ([Mg/(Mg+Fe)]= 89.8-94.2) and high Cr# of spinel (39-71). Secondary, interstitial and undeformed clino- and orthopyroxenes have also been recognized in the harzburgites. These phases indicate melt percolation after partial melting and re-equilibration at lithospheric conditions. Their chemical compositions, *i.e.* low Al_2O_3 and CaO contents in orthopyroxene and very low Na_2O and TiO_2 in clinopyroxene, suggest a possible metasomatic origin from SiO_2-rich fluids and/or depleted melts in a subduction-related setting.

Mineral compositional variations, *e.g.*, Mg# (Ol) *vs.* Cr# (Spl) and Cr# (Spl) *vs.* Mg# (Spl), show that most of the investigated spinel lherzolites plot in the field of abyssal peridotites, while the harzburgites are more akin to fore-arc peridotites (Fig. 2). These features have also been confirmed by whole-rock REE chemistry.

REE patterns of lherzolites are characterised by more or less flat HREE segments and steeply sloping LREE patterns, which are typically observed for abyssal-type peridotites (*i.e.*, Pearce *et al.*, 2000). The harzburgites exhibit very low REE concentrations (REE always below 0.1 times chondritic values) and U-shaped profiles. These features are commonly attributed to fore-arc peridotites that experienced high degrees of fluid-assisted melting (Parkinson & Pearce, 1998; Bizimis *et al.*, 2000).
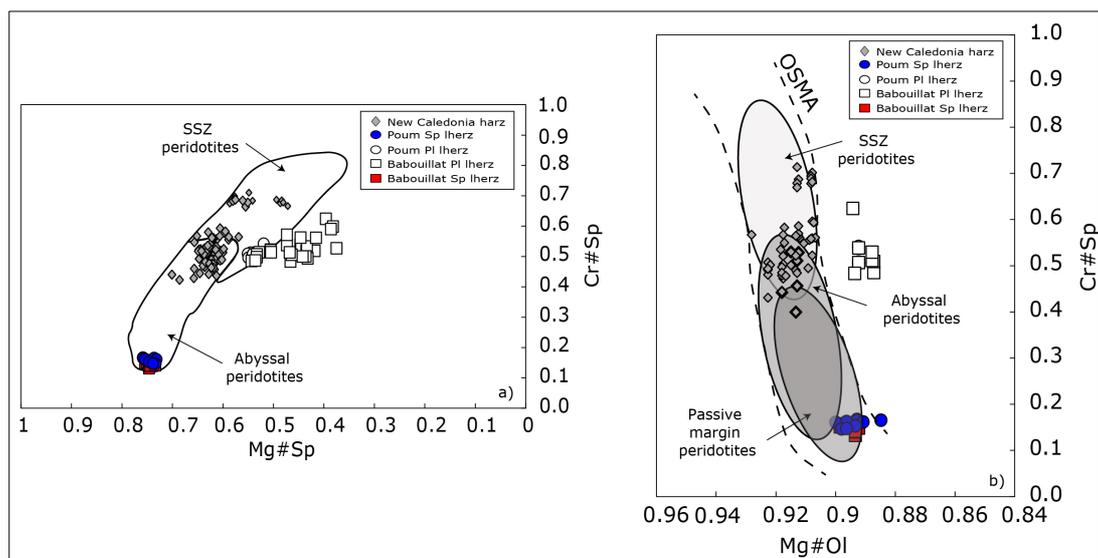
Fig. 2 - Compositional variations of spinels: (a) Cr#-Mg#. Field for abyssal and fore-arc peridotites are taken from Dick & Bullen (1984) and Ishii *et al.* (1992), respectively; (b) Average olivine Mg# and spinel Cr# for spinel and plagioclase lherzolites. The olivine-spinel mantle array (OSMA) is shown by dashed lines. Field for supra-subduction zone, abyssal and passive margins peridotites after Dick & Bullen (1984), Arai (1994), and Pearce *et al.* (2000). Data for the New Caledonia harzburgites are from Secchiari (unpublished PhD thesis data). Data from Secchiari *et al.* (2016).

Trace element melting modelling for spinel lherzolites indicates that their HREE compositions are consistent with a low amount (6-8%) of fractional melting of a DMM source (depleted MORB mantle) in the spinel stability field. However MREE/HREE fractionations, coupled with high Yb_N, suggests that melting began at greater depths, in the garnet stability field (Hellebrand *et al.*, 2002; Müntener *et al.*, 2004).
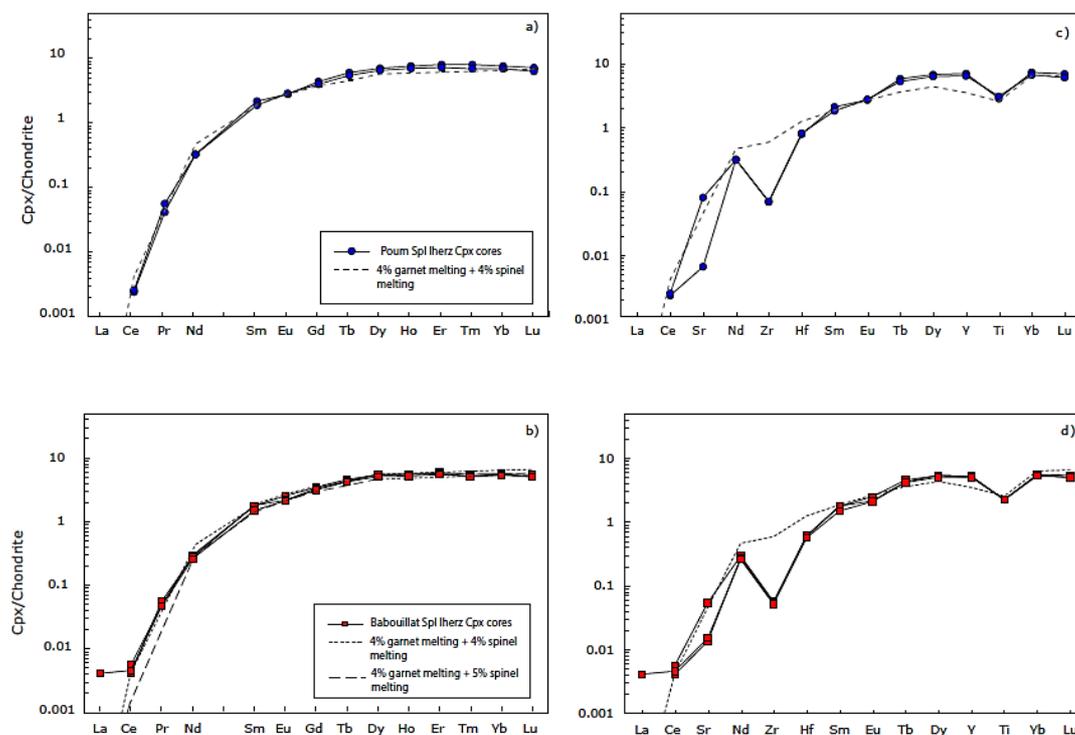

Fig. 3 - Results of fractional melting modelling in the garnet and spinel stability fields for clinopyroxene. All data are chondrite-normalized. DMM Cpx after Hirschmann & Stolper (1996).

Clinopyroxene REE compositions of spinel lherzolites may be reproduced by a two-stages fractional melting event, starting in the garnet stability field (4%), followed by 4-5 % melting in the spinel peridotite field (see Fig. 3, Secchiari *et al.*, 2016).

REE melting modelling for harzburgites shows that the extremely depleted HREE compositions of these rocks can be matched by very high melting degrees (20-25%) of a DMM in the spinel stability field.

Plagioclase lherzolites exhibit melt impregnation microtextures (*i.e.*, interstitial plagioclase, resorbed clinopyroxene in association with plagioclase+orthopyroxene aggregates development), Cr- and TiO_2-enriched spinels and systematical chemical variations with respect to the spinel lherzolites, *i.e.*, whole rock and clinopyroxene REE, Ti, Y, Zr progressive increase. Impregnation models indicate that plagioclase lherzolites may derive from the previously depleted spinel lherzolites by entrapment of highly depleted (non-aggregated) MORB melt fractions in in the shallow oceanic lithosphere (Secchiari *et al.*, 2016).

The studied samples from the mafic sequence are olivine gabbronorites, with textures ranging from allotriomorphic to cumulitic. The main mineralogical features of these rocks, *i.e.*, high Fo content of olivine (87.3-88.9 mol.%), very high Mg# of clinopyroxene (87.7-92.2) and the presence of Ca-rich plagioclase (An = 90-96 mol.%), highlight an origin from primitive, boninitic-like, magma batches in a convergent setting.

Bulk rock compositions are characterized by high Mg# (86-93) and very low incompatible trace element contents (*e.g.*, LREE concentrations mostly below 0.1 times chondrite). They show marked LREE depletion, nearly flat and low HREE (Yb_N = 0.2-0.9) and positive Eu anomalies. The highly depleted nature of these rocks is mirrored by clinopyroxene trace element composition.

The calculated compositions of the putative liquids in equilibrium with the most primitive gabbronorites are consistent with melting of a refractory peridotite source in the spinel stability field. The inferred melts have high Mg# (75-76) and very low REE, Nb, Zr, Hf contents. On the other hand, Ba, Pb, and Sr positive anomalies in the calculated liquids argue for the involvement of a subduction-related component in the magma genesis (König *et al.*, 2010; Li *et al.*, 2013). On a whole, the liquids show geochemical signatures akin to olivine boninite melts with lower absolute concentrations of LREE and other incompatible trace elements (Ba, Pb, Sr, Zr, Hf).

Sr, Nd and Pb isotopic ratios obtained for the New Caledonia ophiolite highlight the presence of a DM source, that suffers different types of processes. Nd isotopes for the lherzolitic lithotypes indicate a derivation from a relatively homogeneous DM reservoir (ε_{Ndi} ranging from +6.98 to +10.97). Nd isotopic data combined with trace element geochemical models do not support a genetic relationship between the lherzolites and the E-MORB belonging to the Poya Unit (Fig. 4). The lherzolites register highly radiogenic Sr and Pb isotopic compositions, related to low-temperature hydrothermal alteration processes.
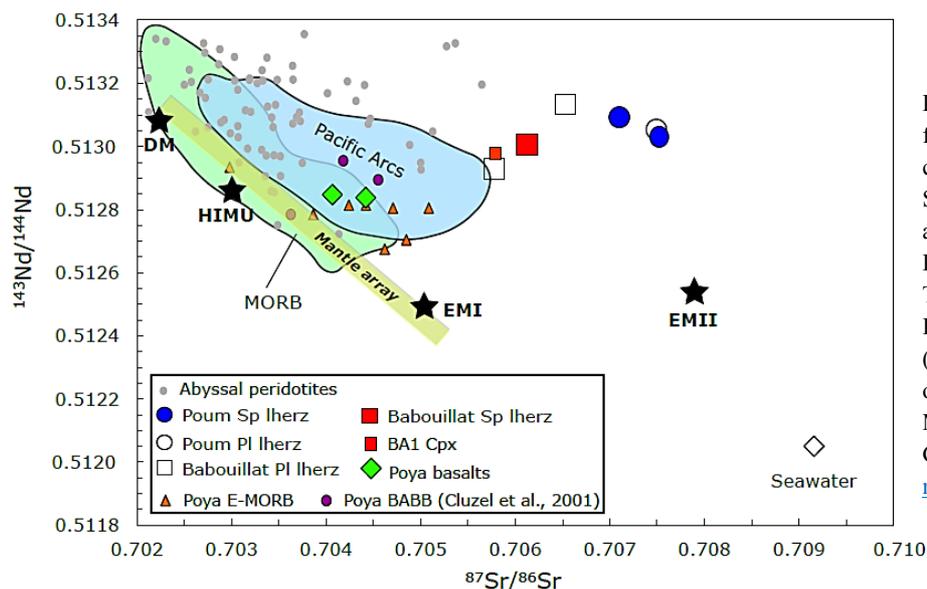

Fig. 4 - $^{143}Nd/^{144}Nd$ *vs.* $^{87}Sr/^{86}Sr$ diagram for lherzolites and Poya basalts. Age-corrected isotopic ratios have been plotted. Sr and Nd seawater isotopic compositions are taken from Palmer & Edmond (1989), Piepgras & Wasserburg (1987), Tachikawa *et al.* (1999). DMM, EMI, EMII and HIMU after Zindler & Hart (1986) and Eisele *et al.* (2002). The field of Pacific arcs includes Izu-Bonin, Tonga, Mariana and Solomon arcs (source: Georoc database http://georoc.mpch-mainz.gwdg.de/georoc/).

The harzburgites exhibit a wider range of Sr, Nd and Pb isotopic ratios, with compositions extending from the DM source toward the EM2 end-member. Sr, Nd and Pb isotopic variations, together with the FME spikes (*i.e.*, Cs, Ba, U, Pb, Sr) observed in the extended trace element diagrams, imply that the harzburgites underwent a source contamination process operated by a subduction-related component.

For gabbronorites, combined trace element chemistry and Sr, Nd, Pb isotopic values indicate a derivation from a homogeneous DM mantle source, affected by a subduction-related fluid contamination.

CONCLUSIONS

From the collected data the following conclusions can be drawn. The New Caledonia peridotites include both relatively undepleted rocktypes (the lherzolites) and refractory lithologies (the harzburgites). These lithotypes experienced different evolutionary scenarios, in various tectonic contexts.

The petrological and geochemical features of the New Caledonia lherzolites indicate a possible origin in a spreading ridge environment, *i.e.*, in a marginal basin formed before Eocenic subduction. This marginal basin was possibly located in the proximity of a transform fault. This finding is supported by the main geochemical characters displayed by the lherzolites (*i.e.*, low melting degree, beginning of the melting in the garnet stability field, close association of spinel and plagioclase lherzolites). Moreover the presence of a major shear zone running along the northeastern side of Belep Islands and the northern lherzolitic massifs of Poum and Tiébaghi has been testified since long time (Nicolas, 1989).

The geochemical and petrological data obtained for the harzburgites show that these lithotypes have an overall ultra-depleted composition, inherited from very high melting degrees. The harzburgites acquired their main geochemical and isotopic fingerprint in a subduction zone environment. Despite their homogeneous composition in terms of major and trace elements, Sr, Nd, and Pb isotopes point out that the harzburgites are not a single homogeneus body. Some harzburgitic massifs were strongly affected by a contamination process operated by a subduction-related component, owing to poorly radiogenic Nd isotopic values and high Pb isotopic ratios, in the range of the Pacific sediments.

The New Caledonia gabbronorites reflect injection of primitive, ultradepleted ("boninite-like") magma batches in the lower forearc crust, possibly before aggregation, during the first phases of arc formation. The heterogeneous Pb isotopic signature of the gabbronorites, as well as the enrichments in FME both for whole rock and clinopyroxene, most likely reflect a subarc asthenospheric mantle source variably modified by subduction-related fluids.

REFERENCES

Aldanmaz, E., Schmidt, M.W., Gourgaud, A., Meisel, T. (2009): Mid-ocean ridge and supra-subduction geochemical signatures in spinel-peridotites from the Neotethyan ophiolites in SW Turkey: Implications for upper mantle melting processes. *Lithos*, **113**, 691-708.

Arai, S. (1994): Characterization of spinel peridotites by olivine-spinel compositional relationships: Review and interpretation. *Chem. Geol.*, **113**, 191-204.

Bizimis, M., Salters, V.J.M., Bonatti, E. (2000): Trace and REE content of clinopyroxenes from supra-subduction zone peridotites. Implications for melting and enrichment processes in island arcs. *Chem. Geol.,* **165**, 67-85.

Choi, S.H., Shervais, J.W., Mukasa, S.B. (2008): Supra-subduction and abyssal mantle peridotites of the Coast Range ophiolite, California. *Contrib. Mineral. Petr.*, **156**, 551-576.

Cluzel, D., Chiron, D., Courme, M.D. (1998): Discordance de l'Eocène supérieur et événements pré-obduction en Nouvelle-Calédonie (Pacifique sud-ouest). *Cr. Acad. Sci. II A*, **327**, 485-91.

Cluzel, D., Aitchison, J., Picard, C., (2001): Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific): geodynamic implications. *Tectonophysics*, **340**, 23-59.

Cluzel, D., Jourdan, F., Meffre, S., Maurizot, P., Lesimple, S. (2012): The metamorphic sole of New Caledonia ophiolite: ^{40}Ar/^{39}Ar, U-Pb, and geochemical evidence for subduction inception at a spreading ridge. *Tectonics*, **31**, 17-27.

Dick, H.J.B. & Bullen, T. (1984): Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. *Contrib Mineral. Petr.*, **86**, 54-76.

Dilek, Y. & Furnes, H. (2011): Ophiolite genesis and global tectonics: Geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *Geol. Soc. Am. Bull.*, **123**, 387-411.

Dupuy, C., Dostal, J., Leblanc, M. (1981): Geochemistry of an ophiolitic complex from New Caledonia. *Contrib. Mineral. Petr.*, **76**, 77-83.

Eisele, J., Sharma, M., Galer, S.J.G., Blichert-Toft, J., Devey, C.W., Hofmann, A. W. (2002): The role of sediment recycling in EM-1 inferred from Os, Pb, Hf, Nd, Sr isotope and trace element systematics of the Pitcairn hotspot. *Earth Planet. Sci. Lett.*, **196**, 197-212.

Eissen, J.-P., Crawford, A.J., Cotten, J., Meffre, S., Bellon, H., Delaune, M. (1998): Geochemistry and tectonic significance of basalts in the Poya Terrane, New Caledonia. *Tectonophysics*, **284**, 203-219.

Hamelin, B., Dupré, B., Allègre, C.J. (1984): The lead isotope systematics of ophiolite complexes. *Earth Planet. Sci. Lett.*, **67**, 351-366.

Hellebrand, E., Snow, J.E., Hoppe, P., Hofmann, A.W. (2002): Garnet-field melting and late-stage refertilization in "residual" abyssal peridotites from the Central Indian Ridge. *J. Petrol.*, **43**, 2305-2338.

Hirschmann, M.M. & Stolper, E.M. (1996): A possible role for garnet pyroxenite in the origin of the "garnet signature" in MORB. *Contrib. Mineral. Petr.*, **124**, 185-208.

Ishii, T., Robinson, P.T., Maekawa, H., Fiske, R. (1992): Petrological studies of peridotites from diapiric serpentinite seamounts in the Izu-Ogasawara-Mariana Forearc, Leg 125. *Proceeding of the Ocean Drilling Program, Scientific Results*, **125**, 445-485.

König, S., Münker, C., Schuth, S., Luguet, A., Hoffmann, J.E., Kuduon, J. (2010): Boninites as windows into trace element mobility in subduction zones. *Geochim. Cosmochim. Ac.*, **74**, 684-704.

Li, Y.-B., Kimura, J.-I., Machida, S., Ishii, T., Ishiwatari, A., Maruyama, S., Qiu, H.-N., Hishikawa, T., Kato, Y., Haraguki, S., Takahata, N., Hirahara, Y., Myaziki, T. (2013): High-Mg Adakite and Low-Ca Boninite from a Bonin Fore-arc Seamount: Implications for the Reaction between Slab Melts and Depleted Mantle. *J. Petrol.*, **54**, 1149-1175.

Marchesi, C., Garrido, C.J., Godard, M., Belley, F., Ferré, E. (2009): Migration and accumulation of ultra-depleted subduction-related melts in the Massif du Sud ophiolite (New Caledonia). *Chem. Geol.*, **266**, 171-186.

Miyashiro, A. (1973): The Troodos ophiolitic complex was probably formed in an island arc. *Earth Planet. Sci. Lett.*, **19**, 218-224.

Müntener, O., Pettke, T., Desmurs, L., Meier, M., Schaltegger, U. (2004): Refertilization of mantle peridotite in embryonic ocean basins: trace element and Nd isotopic evidence and implications for crust-mantle relationships. *Earth Planet. Sci. Lett.*, **221**, 293-308.

Nicolas, A. (1989): Structures of ophiolites and dynamics of oceanic lithosphere. *Petrology and Structural Geology*, **4**, Springer Netherlands, 369 p.

Nicolas, A. & Dupuy, C. (1984): Origin of ophiolitic and oceanic lherzolites. *Tectonophysics*, **110**, 177-187.

Palmer, M.R. & Edmond, J.M. (1989): The strontium isotope budget of the modern ocean. *Earth Planet. Sci. Lett.*, **92**, 11-26.

Parkinson, I.J. & Pearce, J.A. (1998): Peridotites from the Izu-Bonin-Mariana forearc (ODP leg 125): Evidence for mantle melting and melt-mantle interaction in a supra-subduction zone setting. *J. Petrol.*, **39**, 1577-1618.

Pearce, J.A., Lippard, S.J., Roberts, S. (1984): Characteristics and tectonic significance of supra-subduction zone ophiolites. *Geol. Soc. Spec. Publ.*, **16**, 77-94.

Pearce, J.A, Barker, P.F., Edwards, S.J., Parkinson, I.J., Leat, P.T. (2000): Geochemistry and tectonic significance of peridotites from the South Sandwich arc-basin system, South Atlantic. *Contrib. Mineral. Petr.*, **139**, 36-53.

Piepgras, D.J. & Wasserburg, G.J. (1987): Rare-earth element transport in the western North-Atlantic inferred from Nd isotopic observations. *Geochim. Cosmochim. Ac.*, **51**, 1257-1271.

Pirard, C., Hermann, J., O'Neill, H.S.C. (2013): Petrology and Geochemistry of the Crust-Mantle Boundary in a Nascent Arc, Massif du Sud Ophiolite, New Caledonia, SW Pacific. *J. Petrol.*, **54**, 1759-1792.

Prinzhofer, A. & Allègre, C. (1985): Residual peridotites and the mechanisms of partial melting. *Earth Planet. Sci. Lett.*, **74**, 251-265.

Prinzhofer, A., Nicolas, A., Cassard, D., Moutte, J., Leblanc, M., Paris, J.P., Rabinovitch, M. (1980): Structures in the new caledonia peridotites-gabbros: Implications for oceanic mantle and crust. *Tectonophysics*, **69**, 85-112.

Secchiari, A., Montanini, A., Bosch, D., Macera, P., Cluzel, D. (2016): Melt extraction and enrichment processes in the New Caledonia lherzolites: Evidence from geochemical and Sr-Nd isotope data. *Lithos*, http://dx.doi.org/10.1016/j.lithos.2016.04.030

Tachikawa, K., Jeandel, C., Roy-Barman, M. (1999): A new approach to the Nd residence time in the ocean: the role of atmospheric inputs. *Earth Planet. Sci. Lett.*, **170**, 433-446.

Ulrich, M., Picard, C., Guillot, S., Chauvel, C., Cluzel, D., Meffre, S. (2010): Multiple melting stages and refertilization as indicators for ridge to subduction formation: The New Caledonia ophiolite. *Lithos*, **115**, 223-236.

Whattam, S.A. (2009): Arc-continent collisional orogenesis in the SW Pacific and the nature, source and correlation of emplaced ophiolitic nappe components. *Lithos*, **113**, 88-114.

Zindler, A. & Hart, S.R. (1986): Chemical geodynamics. *Annu. Rev. Earth Pl. Sci.*, **14**, 493-571.