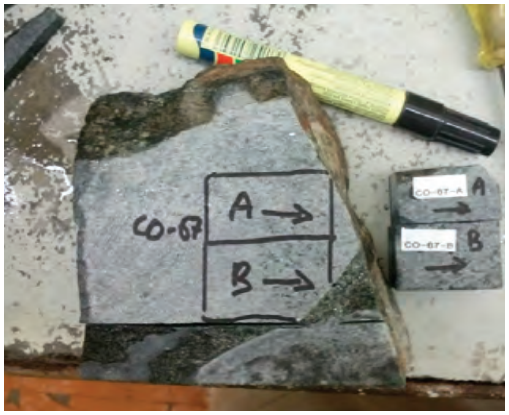
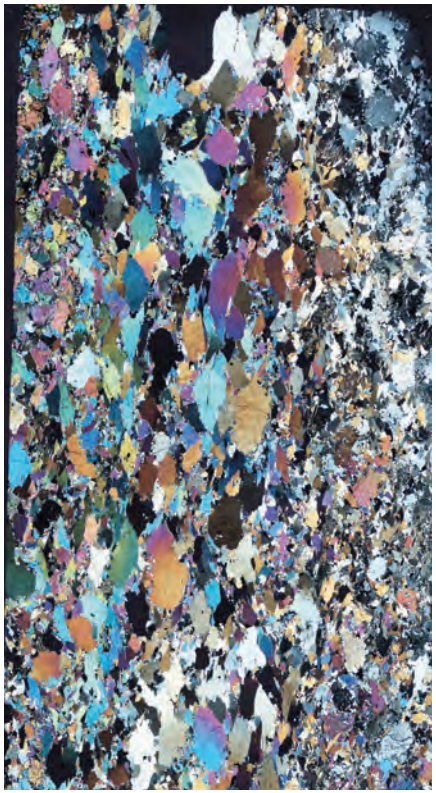
Appendix 3:
Cabo Ortegal Sample Collection

Note: All thin sections and drawings of block location on the sample are 27x46 mm.





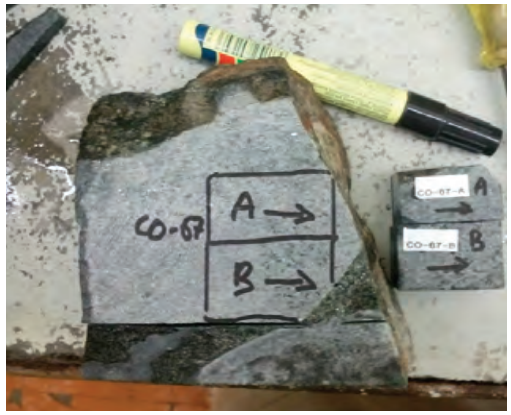
CO67A

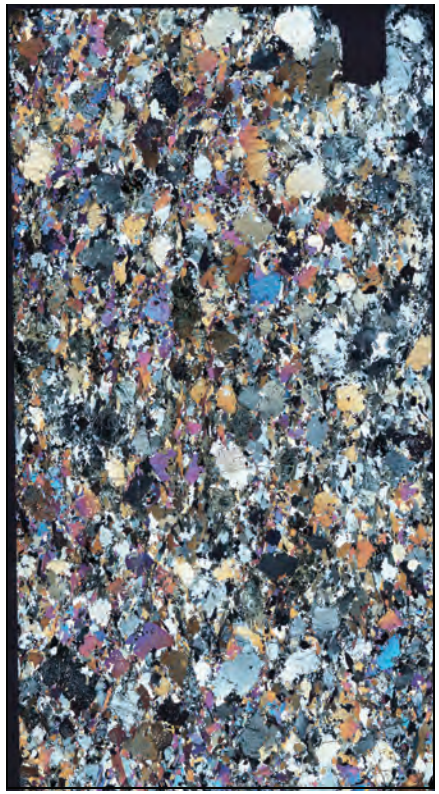
Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, sulfide

Texture: Changes across the section

Observations: *Type-3* pyroxenite, Bands of large euhedral amphiboles visible between two sections that are more porphyroclastic





CO67B

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, sulfide

Texture: Porphyroclastic but can look equigranular in some parts

Observations: *Type-3* pyroxenite
The growth of amphibole gives an impression of a more equilibrated texture for pyroxenes than what it is

CO96AA

Lithology: Pyroxenite

Minerals: Opx, cpx, olivine, amphibole spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-1* pyroxenite, very clear porphyroclastic texture

CO96AB

Lithology: pyroxenite

Minerals: opx, cpx, olivine, amphibole spinel, sulfide

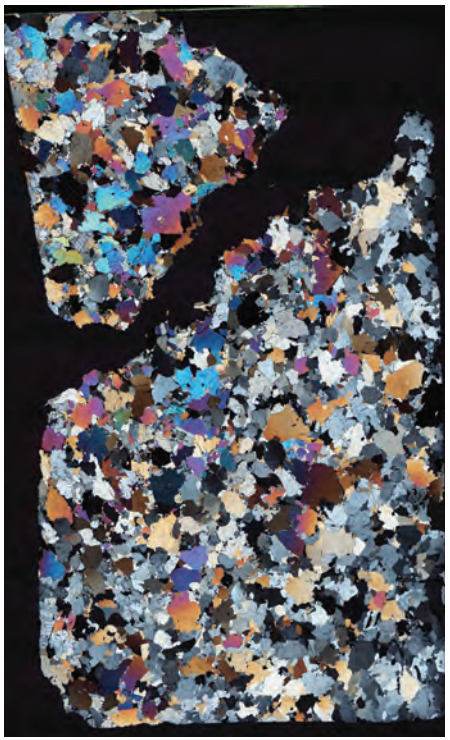
Texture: Porphyroclastic

Observations: *Type-1* pyroxenite

CO97A

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, spinel, sulfide



Texture: Porphyroclastic

Observations: *Type-2* pyroxenite, The bimodal size distribution is not as strong as in other samples

CO99A

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-2* pyroxenite

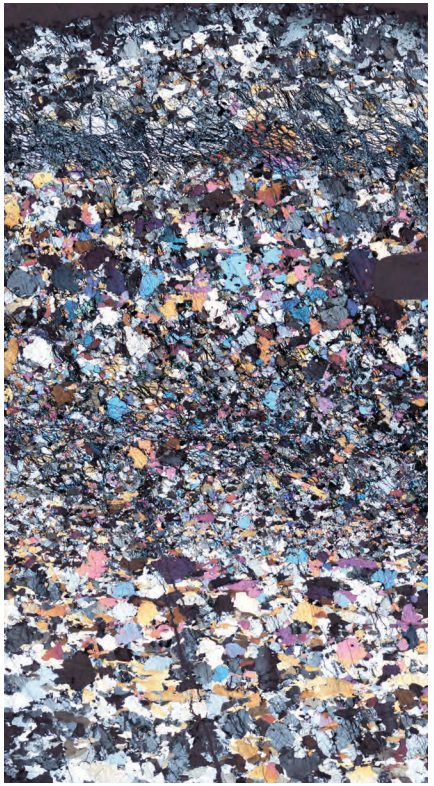
CO100A

Lithology: Pyroxenite

Minerals: Opx, cpx, olivine, spinel, amphibole, sulfide

Texture: Porphyroclastic

Observations: *Type-1* pyroxenite olivine-rich horizons are clearly visible thanks to the late serpentine overprint



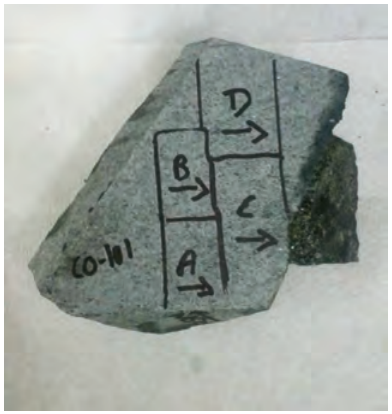
CO100B

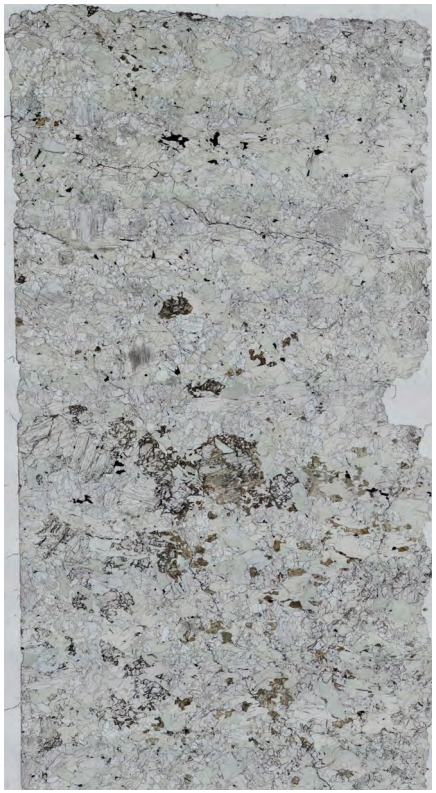
Lithology: Pyroxenite

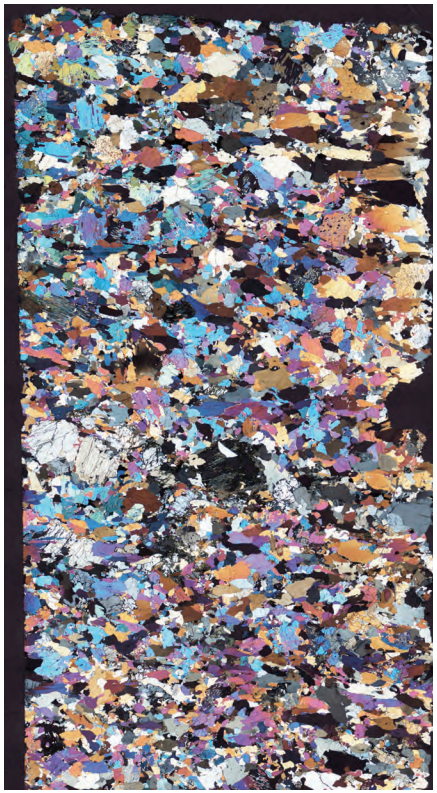
Minerals: Opx, cpx, olivine, spinel, amphibole, sulfide

Texture: Porphyroclastic

Observations: *Type-1* pyroxenite, olivine-rich horizons are very visible







CO101C

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, sulfide

Texture: Equigranular

Observations: *Type-3* pyroxenite
Texture looks equilibrated because of the amphibole growth

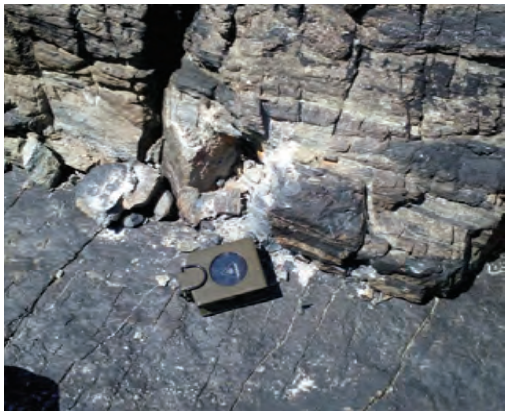
401A

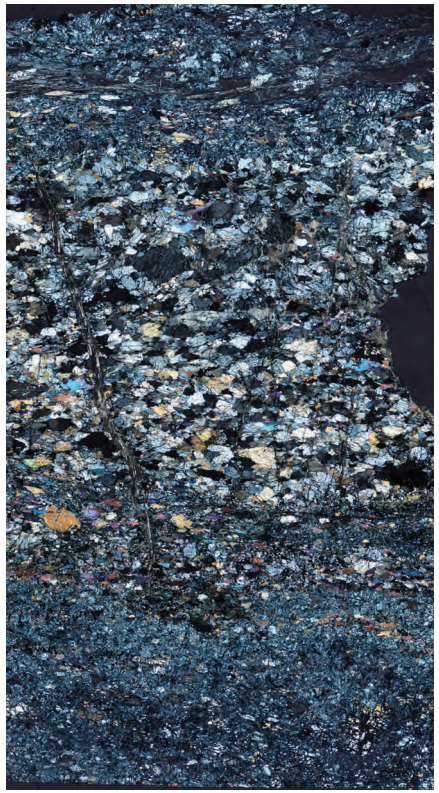
Lithology: Pyroxenite

Minerals: Opx, cpx, olivine, amphibole, spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-1* pyroxenite
Visible grain size reduction at the contact with the host dunite (top)





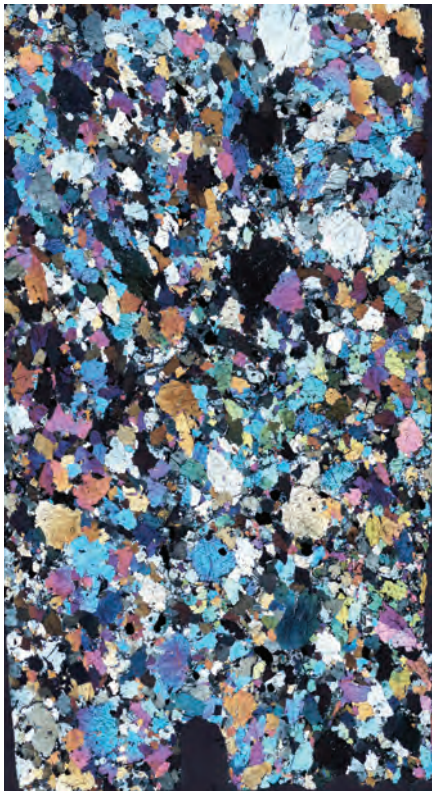
602C

Lithology: Orthopyroxenite

Minerals: Opx, cpx, monticellite, amphibole, spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-4* pyroxenite Better-preserved layer from that sample. Cross-cutting of serpentine veins through the pyroxenite are visible and indicate a stronger viscosity for the pyroxenite in the serpentine stability domain.



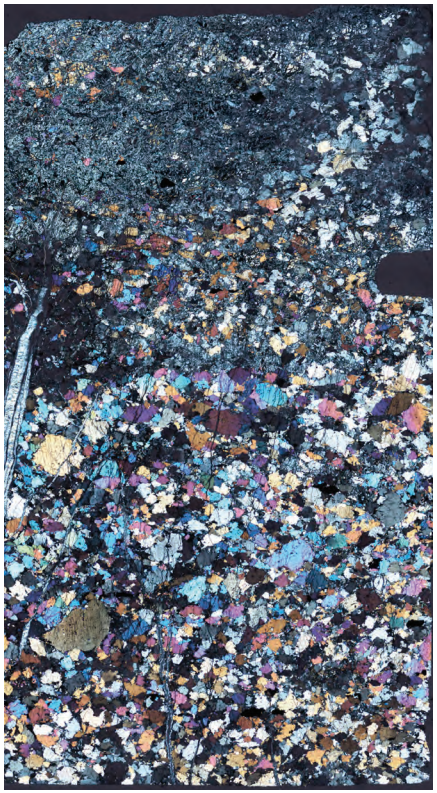
701BA

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, spinel, sulfide, olivine

Texture: Granoblastic

Observations: *Type-1* pyroxenite
No olivine-rich layers are visible here but interstitial olivines are present



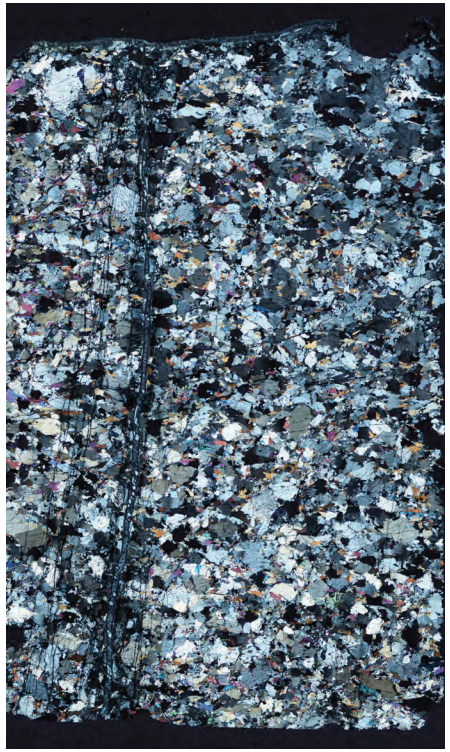
702A

Lithology: Pyroxenite

Minerals: Opx, cpx, olivine, amphibole spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-1* pyroxenite, with interstitial olivine in between pyroxenes



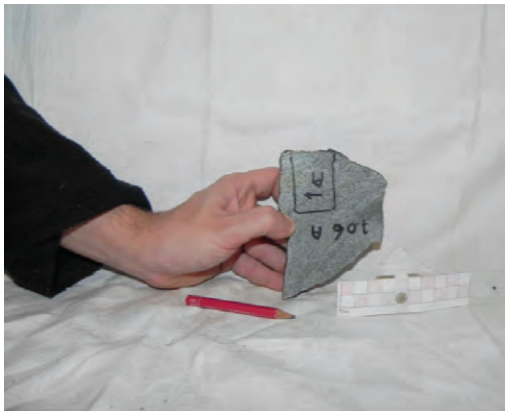
704A

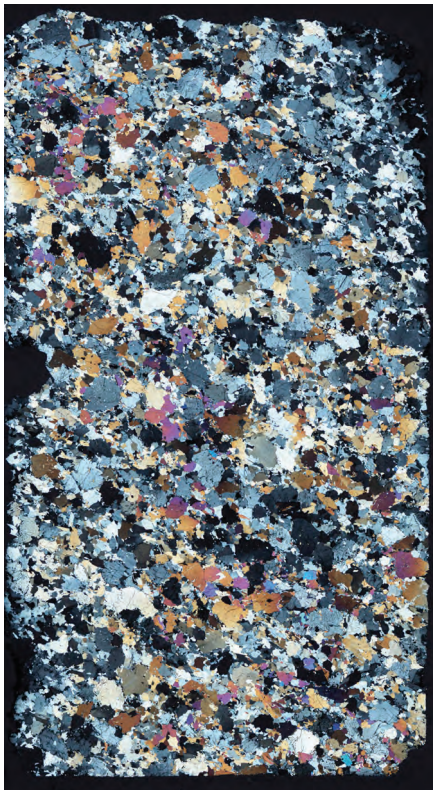
Lithology: Orthopyroxenite

Minerals: Opx, olivine, cpx, amphibole, spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-4* pyroxenite
Layer thickness is decimetric





706AA

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, spinel, sulfide

Texture: Porphyroclastic

Observations: *Type-2* pyroxenite, most likely amongst the freshest samples collected

Appendix 4:
Trinity Sample Collection

Note: All thin sections and drawings of block location on the sample are 27x46 mm.

01T12A

Lithology: Layered cumulates

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equilibrated equigranular

01T13A

Lithology: Layered cumulates

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equilibrated equigranular

01T13B

Lithology: Layered cumulate

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equigranular and equilibrated

01T13C

Lithology: Layered cumulate

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equigranular and equilibrated

Observations: Finely layered cumulate in contact with coarser lithology at the top of the section

03T16A

Lithology: Pegmatite
(i.e. coarse-grained fraction)

Minerals: Cpx, olivine, opx, amphibole

Texture: Coarse grained

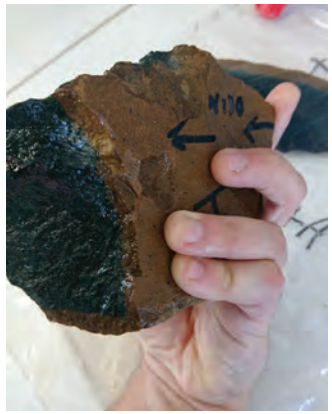
Observations: Large euhedral grains of cpx associated with smaller cpx, opx and olivine matrix

03T46B

Lithology: Layered cumulate

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equigranular and equilibrated



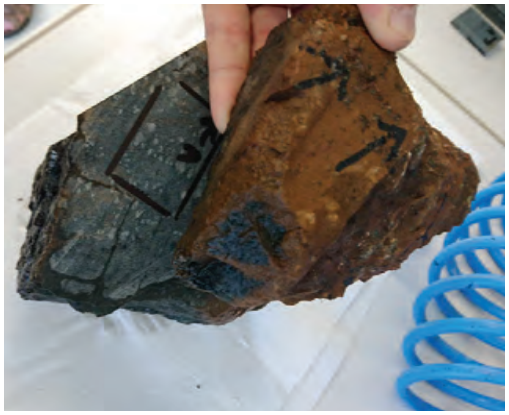
17T4AA

Lithology: Dunite

Minerals: Olivine, spinel

Texture: Equilibrated equigranular

Observations: Foliation was invisible, lineation marked by spinel



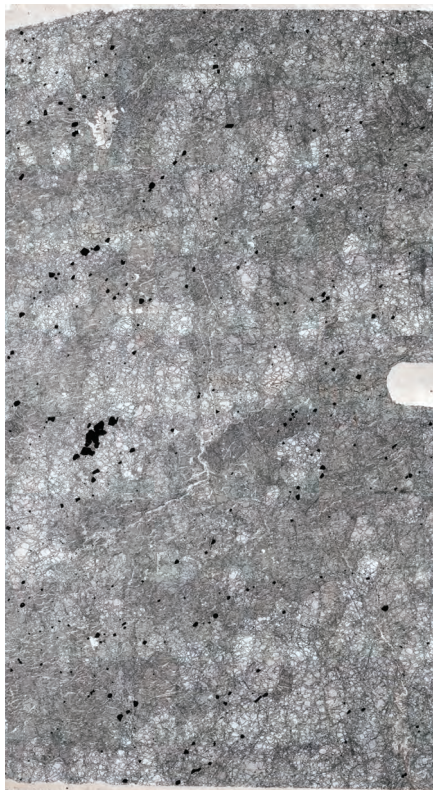
17T4EA

Lithology: Lherzolite

Minerals: Olivine, opx, cpx, spinel

Texture: Equilibrated, bimodal grain size

Observations: Larger and smaller grains are located next to the pyroxene aggregates



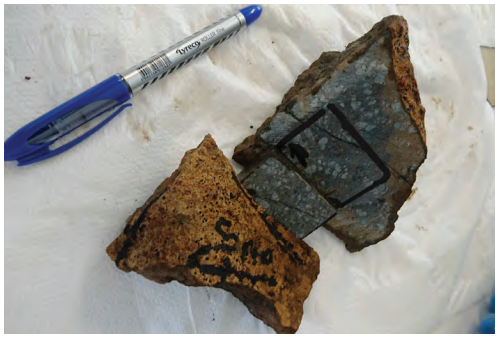
17T25EA

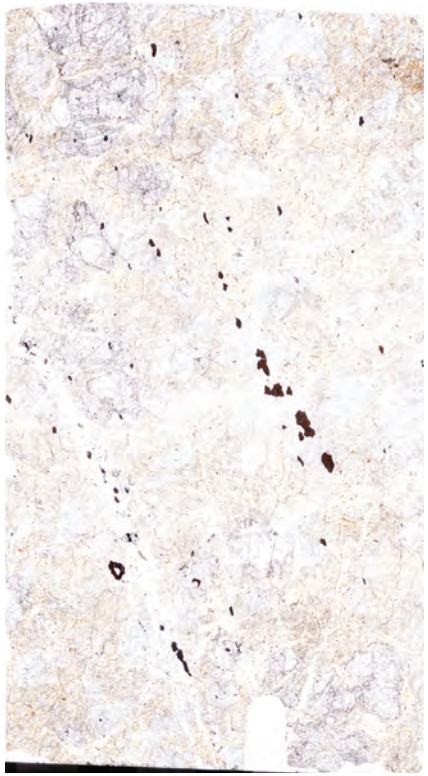
Lithology: Dunite

Minerals: Olivine, spinel

Texture: Granoblastic

Observations: recrystallised texture close to textural equilibrium





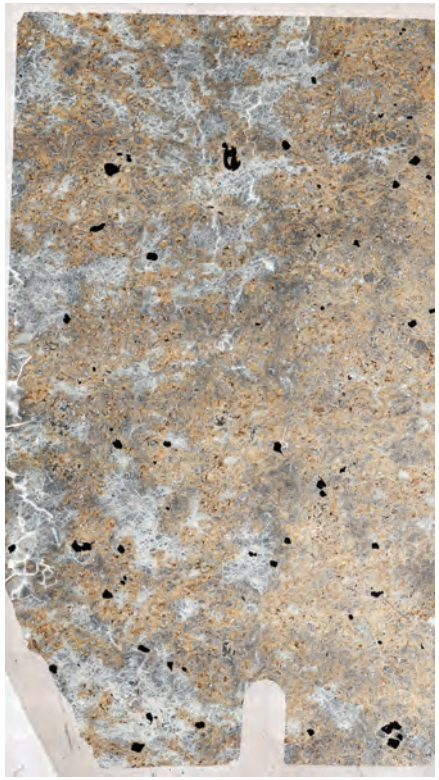
T1LD1A

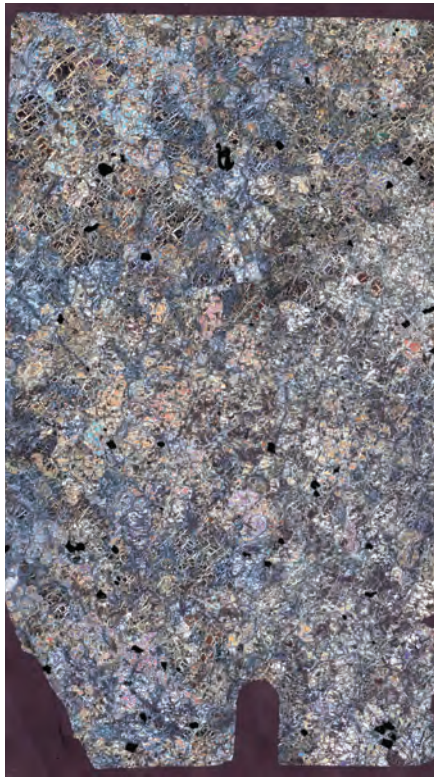
Lithology: Harzburgite

Minerals: Olivine, opx, spinel

Texture: Equilibrated with bimodal grain-size distribution

Observations: Structural framework was visible with aligned opx and spinel





T1LD2A

Lithology: Dunite

Minerals: Olivine, spinel

Texture: Corse-grained and equilibrated

Observations: Strong serpentinisation, only lineation is visible.

T2VB3A

Lithology: Lherzolite

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equilibrated with bimodal grain-size distribution

Observations: Structural framework unclear

T2VB4B

Lithology: Lherzolite and pyroxenite

Minerals: Opx, cpx, olivine, spinel, amphibole

Texture: Equilibrated and close to equigranular

Observations: Texture is equigranular in both lherzolite and pyroxenite

T3BC1A

Lithology: Layered cumulates

Minerals: Opx, cpx, olivine, amphibole, spinel

Texture: Equigranular equilibrated

Observations: Layered cumulates, lineation not visible

T3BC3A

Lithology: Pyroxenite

Minerals: Opx, cpx, amphibole, olivine, spinel

Texture: Equigranular and equilibrated

Observations: Macrocryst of opx perturbating the layering

T3BC4A

Lithology: Massive pyroxenite

Minerals: Cpx, olivine, spinel

Texture: Unequilibrated with a bimodal grain distribution

Observations: olivine-rich layers are rarely visible on the field

T4BC2A

Lithology: Lherzolite and pyroxenite

Minerals: Olivine, cpx, opx, spinel, amphibole

Texture: Porphyroclastic

Observations: Strongly serpentinised lherzolite. Pyroxenite is fresher.

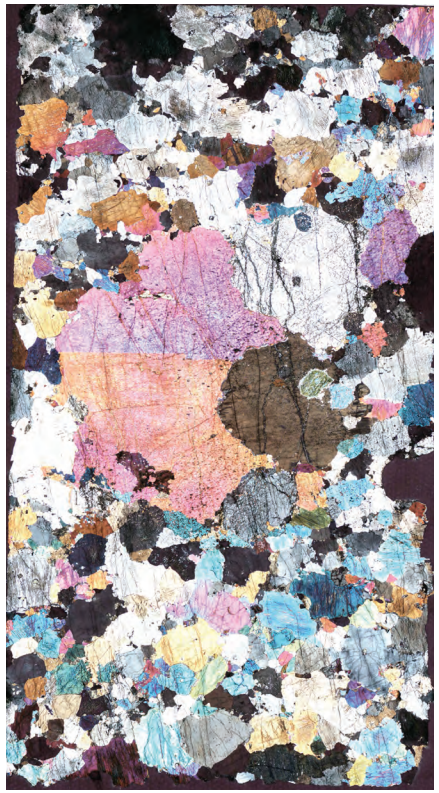
T4BC3A

Lithology: Lherzolite

Minerals: Opx, cpx, olivine, spinel

Texture: Porphyroclastic

Observations: Strongly serpentinised, 2 vertical meters below the layered cumulates



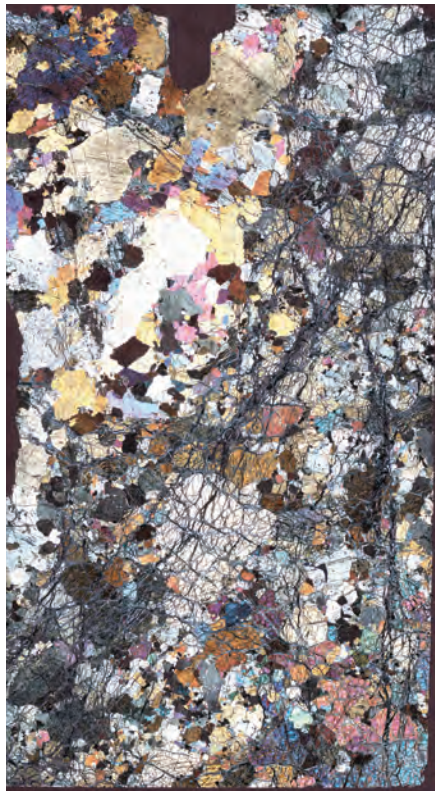
T4BC4A

Lithology: Massive Pyroxenite

Minerals: Cpx, amphibole

Texture: Unequilibrated with bimodal grain size

Observations: Large twinned cpx, close to T3BC4A



T4BC6A

Lithology: Peridotite and pyroxenite

Minerals: Olivine, cpx, opx, amphibole, spinel

Texture: Equilibrated with bimodal distribution

Observations: Peridotite xenolith in massive pyroxenites

T4BC7B

Lithology: Websterite

Minerals: Olivine, cpx, opx, spinel amphibole

Texture: Porphyroclastic

Observations: Last outcrop of cross-section for layered cumulates, strongly serpentinised

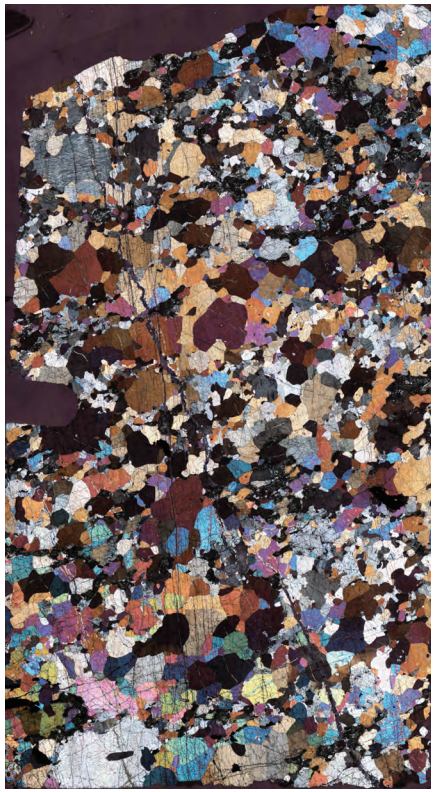
T4BC8A

Lithology: Layered cumulates

Minerals: Olivine, opx, cpx, spinel, amphibole

Texture: Equilibrated equigranular

Observations: Tilted bending, a few hundred meters away from the main cross section



T5CP1A

Lithology: Lherzolite

Minerals: Olivine, cpx, opx, spinel, plagioclase

Texture: Equilbrated equigranular

Observations: Plagioclase-bearing lherzolite with strong deformation visible in the field

T5CP2A

Lithology: Dunite and pyroxenite

Minerals: Olivine, cpx, opx, amphibole, spinel

Texture: Equilibrated equigranular

Observations: Pyroxenite level in dunite. Dunite texture is equilibrated and equigranular. Pyroxenite texture has a more bimodal grain size distribution.

Appendix 5: Publications

Direct output from the thesis:

Henry, H., Tilhac, R., Griffin, W.L., O'Reilly, S.Y., Satsukawa, T., Kaczmarek, M.-A., Grégoire, M., Ceuleneer, G., 2017. Deformation of mantle pyroxenites provides clues to geodynamic processes in subduction zones: Case study of the Cabo Ortegal Complex, Spain. **Earth and Planetary Science Letters** 472, 174-185.

Collaboration relevant to the Cabo Ortegal pyroxenites:

Tilhac, R., Ceuleneer, G., Griffin, W.L., O'Reilly, S.Y., Pearson, N.J., Benoit, M., **Henry, H.**, Girardeau, J., Grégoire, M., 2016. Primitive Arc Magmatism and Delamination: Petrology and Geochemistry of Pyroxenites from the Cabo Ortegal Complex, Spain. **Journal of Petrology** 57, 1921-1954.

Tilhac, R., Grégoire, M., O'Reilly, S.Y., Griffin, W.L., **Henry, H.**, Ceuleneer, G., 2017. Sources and timing of pyroxenite formation in the sub-arc mantle: Case study of the Cabo Ortegal Complex, Spain. **Earth and Planetary Science Letters** 474, 490-502.

Collaboration on other ultramafic domains, EBSD analysis, data processing with Matlab and microstructure interpretations:

Xiong, Q., **Henry, H.**, Griffin, W. L., Zheng, J.-P., Satsukawa, T., Pearson, N. J., and O'Reilly, S. Y., 2017, High- and low-Cr chromitite and dunite in a Tibetan ophiolite: evolution from mature subduction system to incipient forearc in the Neo-Tethyan Ocean: **Contributions to Mineralogy and Petrology**, v. 172, no. 6.

Earth and Planetary Science Letters 472 (2017) 174–185

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Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Deformation of mantle pyroxenites provides clues to geodynamic processes in subduction zones: Case study of the Cabo Ortegal Complex, Spain

Hadrien Henry [a,b,*], Romain Tilhac [a,b], William L. Griffin [a], Suzanne Y. O'Reilly [a], Takako Satsukawa [a,c], Mary-Alix Kaczmarek [d,b], Michel Grégoire [a,b], Georges Ceuleneer [b]

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ABSTRACT

In the Herbeira massif, Cabo Ortegal Complex, Spain, a well exposed assemblage of deformed dunites and pyroxenites offers a unique opportunity to investigate key upper mantle tectonic processes. Four types of pyroxenites are recognized: clinopyroxenites with enclosed dunitic lenses (*type-1*), massive websterites (*type-2*), foliated and commonly highly amphibolitized clinopyroxenites (*type-3*) and orthopyroxenites (*type-4*). Field and petrological observations together with EBSD analysis provide new insights on the physical behavior of the pyroxenes and their conditions of deformation and reveal the unexpected journey of the Cabo Ortegal pyroxenites.

We show that, during deformation, *type-1* pyroxenites, due to their enclosed dunitic lenses, are more likely to localize the deformation than *types-2* and *-4* pyroxenites and may latter act as preferred pathway for fluid/melt percolation, eventually resulting in *type-3* pyroxenites. All pyroxenite types display a similar response to deformation. Orthopyroxene deformed mostly by dislocation creep; it shows kink bands and undulose extinction and its fabric is dominated by [001](100). Clinopyroxene displays subgrain rotation, dynamic recrystallization and fabric with [010] axes clustering next to the foliation pole and [001] axes clustering next to the lineation suggesting activation of [001](110) and [001](100) in some samples. These observations are in good agreement with deformation at temperatures greater than 1000 °C. Olivine in *type-1* and *type-4* pyroxenites shows [100](010) or [001](010) fabrics that are consistent with deformation at temperatures >1000 °C and may indicate deformation in a hydrous environment. The amphibole [001](100) fabric gives insights on a lower-temperature deformation episode (~800 to 500 °C). Our results, interpreted in the light of published experimental data, together with the regional geological and geochemical studies are consistent with the following tectonic evolution of the Cabo Ortegal pyroxenites: (1) delamination from an arc root in a mantle-wedge setting at temperatures above 1000 °C and (2) introduction into a relatively softer subduction channel where deformation was accommodated by localized shear zones, thus preserving the high-temperature fabrics of pyroxenites. The Cabo Ortegal pyroxenites may therefore be seen as a rare exposure of deformed mantle-wedge material.

1. Introduction

Rheological models of the upper mantle traditionally adopt a major assumption: the physical properties of mantle peridotites can be satisfactorily inferred from those of olivine. This working hypothesis is being challenged by studies highlighting the potentially important volume of pyroxenes, in the shallow upper mantle and from the transition zone to the crust. Evenly-distributed pyroxenes may modify the bulk rheological properties of peridotites, compared to an unrealistic assemblage of pure olivine, and partly condition their behavior during penetrative deformation. On the other hand, local concentrations of pyroxenes (e.g. layering) may influence the distribution of deformation and lead *inter alia* to

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Sources and timing of pyroxenite formation in the sub-arc mantle: Case study of the Cabo Ortegal Complex, Spain

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ABSTRACT

Pyroxenites exposed in ophiolites and orogenic peridotite massifs may record petrogenetic processes occurring in mantle domains generated and/or transferred in supra-subduction environments. However, the timing of their formation and the geochemical characteristics of their source region commonly are obscured by metamorphic and metasomatic overprints. This is especially critical in arc-related environments, where pyroxenites may be formed during the differentiation of primitive magmas. Our approach combines Sr- and Nd-isotope geochemistry and geochronology, and modelling of REE diffusion, to further constrain the origin of a well-characterized set of pyroxenites from the arc-related Cabo Ortegal Complex, Spain. In the light of petrological constraints, Sr- and Nd-isotope systematics consistently indicate that cpx and amphibole have acquired disequilibrium during two main episodes: (1) a magmatic/metasomatic episode that led to the formation of the pyroxenites, coeval with that of Cabo Ortegal granulites and corresponding to the incipient stage of a potential Cadomian arc (459–762 Ma; isochron and second-stage Nd model ages); (2) an episode of metamorphic amphibolitization upon the percolation of relatively unradiogenic and LREE-enriched hydrous fluids, subsequent to the delamination of the pyroxenites from their arc-root settings during Devonian subduction. Calculations of diffusional timescale for the re-equilibration of REE are consistent with this scenario but provide only poor additional constraints due to the sensitivity of this method to grain size and sub-solidus temperature. We thus emphasize the necessity to combine isochron ages and Nd model ages corrected for radiogenic ingrowth to put time constraints on the formation of subduction- and/or collision-related pyroxenites, along with petrological and geochemical constraints. Homogeneous age-corrected $^{143}Nd/^{144}Nd$ of 0.5121–0.5125 (ε_{Nd} between 0 and +7.5) and $^{87}Sr/^{86}Sr$ of 0.7037–0.7048 provide information on the sources of the metasomatic agents involved (and potentially the parental melts) and notably indicate the contributions from enriched mantle components (EM I and/or II). This suggests the involvement of an old crustal component, which is consistent with the derivation of the pyroxenites and granulites from an ensialic island arc, potentially built on the northern margin of either Gondwana or a pre-Gondwanan continental block. This case study thus documents the role of melt–rock reactions as major pyroxenite-forming processes in the sub-arc mantle, providing further constraints on their sources and timing in the Cabo Ortegal Complex.

1. Introduction

The mineralogical and geochemical diversity of pyroxenites observed in peridotite massifs and xenoliths provides a unique record of the petrological processes contributing to the evolution of lithospheric mantle domains (Downes, 2007, for a review). Despite their minor abundance, their geodynamic significance is strengthened by their implication in the petrogenesis and transfer of mantle-derived magmas in various tectonic environments (e.g. Sobolev et al., 2007). Different types of mantle pyroxenites have been reported, representing crystallized products of *in-situ* partial melting or metamorphic segregations of peridotites (e.g. Dick and Sinton, 1979), metamorphosed products of recycled oceanic lithosphere (Allègre and Turcotte, 1986) and high-pressure crystal cumulates from migrating mantle melts (e.g. Bodinier et al., 1987). Studies of exhumed mantle terranes, such as Ronda (Spain),

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Original Article

OXFORD

Primitive Arc Magmatism and Delamination: Petrology and Geochemistry of Pyroxenites from the Cabo Ortegal Complex, Spain

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ABSTRACT

The genesis of primitive arc magmas has had a major impact on continent formation through time, but the rarity of exposures of deep arc sections limits our understanding of the details of melt migration and differentiation. Abundant pyroxenites are exposed within a 600 m thick section of arc-related mantle harzburgites and dunites in the Herbeira massif of the Cabo Ortegal Complex, Spain. We report a combination of field and petrographic observations with *in situ* and whole-rock geochemical studies of these pyroxenites. After constraining the effects of secondary processes (serpentinization, fluid or melt percolation and amphibolitization), we determine that the low Al content of pyroxenes, high abundance of compatible elements and the absence of plagioclase reflect melt–peridotite interaction and crystal segregation from primitive hydrous melts at relatively low pressure (<1·2 GPa). Olivine clinopyroxenites and olivine websterites preserving dunite lenses (type 1 and 3 pyroxenites) represent the products of partial replacement of peridotites at decreasing melt/rock ratio following the intrusion of picritic melts. Massive websterites (type 2) may represent the final products of this reaction at higher melt/rock ratios. They crystallized from more Si-rich (boninitic) melts, potentially generated through differentiation of the initially picritic melts or intruded as dykes and veins. Rare opx-rich websterites (type 4) were produced by interaction of these melts with dunites. Chromatographic re-equilibration accompanied late-magmatic crystallization of amphibole from migrating or trapped residual melts. This percolative fractional crystallization produced a range of rare earth element (REE) patterns from spoon-shaped in type 1 pyroxenites to strongly light REE (LREE)-enriched in type 2 and 3 pyroxenites. Particularly high CaO/Al_2O_3 ratios (2·2–11·3) and the selective enrichment of large ion lithophile elements (LILE) over high field strength elements (HFSE) in Cabo Ortegal pyroxenites suggest the generation of Ca-rich picritic–boninitic parental melts via low-degree, second-stage melting of a refractory lherzolite at <2 GPa, following percolation of slab-derived fluids and/or carbonatite melts. Pyroxenites and their host peridotites record high-temperature deformation followed by the development of sheath folds and mylonites. Peak metamorphism was then reached under eclogite-facies conditions (1·6–1·8 GPa and 780–800 °C) as recorded by undeformed garnet coronas around spinel. We suggest that this episode corresponds to the delamination of an arc root owing to gravitational instabilities arising from the presence of abundant pyroxenites within mantle harzburgites. Retrograde metamorphism and hydration under amphibolite-facies conditions were recorded by abundant post-kinematic amphibole, which corresponds to the exhumation of the arc root after its intrusion into a subduction zone. The Cabo Ortegal Complex thus preserves

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ORIGINAL PAPER

High- and low-Cr chromitite and dunite in a Tibetan ophiolite: evolution from mature subduction system to incipient forearc in the Neo-Tethyan Ocean

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Abstract The microstructures, major- and trace-element compositions of minerals and electron backscattered diffraction (EBSD) maps of high- and low-Cr# [spinel Cr# = $Cr^{3+}/(Cr^{3+} + Al^{3+})$] chromitites and dunites from the Zedang ophiolite in the Yarlung Zangbo Suture (South Tibet) have been used to reveal their genesis and the related geodynamic processes in the Neo-Tethyan Ocean. The high-Cr# (0.77–0.80) chromitites (with or without diopside exsolution) have chromite compositions consistent with initial crystallization by interaction between boninitic magmas, harzburgite and reaction-produced magmas in a shallow, mature mantle wedge. Some high-Cr# chromitites show crystal-plastic deformation and grain growth on previous chromite relics that have exsolved needles of diopside. These features are similar to those of the Luobusa high-Cr# chromitites, possibly recycled from the deep upper mantle in a mature subduction system. In contrast, mineralogical, chemical and EBSD features of the Zedang low-Cr# (0.49–0.67) chromitites and dunites and the silicate inclusions in chromite indicate that they formed by rapid interaction between forearc basaltic magmas (MORB-like but with rare subduction input) and the Zedang harzburgites in a dynamically extended, incipient forearc lithosphere. The evidence implies that the high-Cr# chromitites were produced or emplaced in an earlier mature arc (possibly Jurassic), while the low-Cr# associations formed in an incipient forearc during the initiation of a new episode of Neo-Tethyan subduction at ~130–120 Ma. This two-episode subduction model can provide a new explanation for the coexistence of high- and low-Cr# chromitites in the same volume of ophiolitic mantle.

Keywords High- and low-Cr chromitite and dunite · Tibetan ophiolites · Compositions and microstructures of chromitites · Melt–peridotite interaction · Subduction episodes in Neo-Tethyan Ocean

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Introduction

The composition of chromite in ophiolitic chromitites and associated dunites is sensitive to the nature of reactant magmas and peridotites, and hence can be used to track tectonic environments and melt–peridotite (including melt–melt) interaction in the upper mantle (e.g., Dick and Bullen 1984; Arai 1992; Zhou and Robinson 1997; Barnes and Roeder 2001; Kamenetsky et al. 2001; Rollinson 2008; Gonzalez-Jimenez et al. 2011, 2014; Arai and Miura 2016). However, the coexistence of high- and low-Cr# [spinel Cr# = atomic $Cr^{3+}/(Cr^{3+} + Al^{3+})$] chromitites with