Evidence for a Heterogeneous Upper Mantle in the Cabo Ortegal Complex, Spain

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A well-preserved fragment of a heterogeneous upper mantle is present in the Cabo Ortegal Complex (Spain). This section is made of harzburgite containing a large volume of pyroxenite. The pyroxenite is concentrated in a layer 300 meters thick by 3 kilometers long. In this layer, ultramafic rocks, essentially pyroxenite (massive websterite and clinopyroxenite) and minor dunite, alternate without any rhythmicity. Part of this layering is of primary magmatic origin and possibly resulted from crystallization of magmas in dikes intruded into the host peridotite under mantle conditions.

STUDIES OF ULTRAMAFIC INCLUSIONS in lavas and of ultramafic rocks in orogenic massifs have shown that pyroxenites (*1*) are an important constituent of the earth's upper mantle. Pyroxenites are believed to have witnessed partial melting, fractional crystallization, and melt migration processes in the mantle and, hence, to provide evidence of large geochemical heterogeneities in the upper mantle and in its partial melting products. Several interpretations have been proposed for their formation, which requires concentration of pyroxene during crystallization or removal of other minerals by melting, and their origin is still debated. These rocks have been considered as crystallized melts formed by partial melting of the host peridotite (*2*), crystal fractionation products of ultramafic magmas that crystallized in magma chambers under mantle conditions (*3*), crystal fractionation segregates formed by dynamic flow crystallization in magma conduits (*4–7*), and elongated slices of subducted oceanic crust recycled by convection into the mantle (*8*). On the basis of their abundance in peridotite massifs, pyroxenites probably make up only a few percent by volume of the upper mantle. They are scarce in harzburgitic massifs, where they constitute scattered, thin (generally less than 10 cm thick) and discontinuous layers, and mostly occur in the high-temperature lherzolitic massifs such as Beni-Bousera, Freychinède, Lanzo, Lherz, Ronda, or Tinaquillo massifs (*2–4, 6, 9*). In these massifs, pyroxenites form layers a few to several tens of centimeters thick, and locally are concentrated in bands of a few tens of meters in thickness. The pyroxenites are locally associated with gabbros, which may constitute thick layers as in the Fineiro massif (*10*).

In this report, we describe the lithological characteristics of a large pyroxenite layer, at least 300 m thick by 3 km long, in amphibole-bearing harzburgite in the Cabo Ortegal catazonal complex of northwestern Spain (Fig. 1). This large pyroxenite layer is primarily exposed on the 600-m-high western cliff of the Herbeira ultramafic massif. This complex comprises peridotite associated with high-pressure granulite and eclogite, gneiss, and various mafic rocks (*11, 12*). Until recently, the whole complex was thought to be a subautochthonous rift system. The eclogite and granulite were thought to represent the lower part of precambrian continental crust that was intruded by the peridotite (*13–16*). Recent structural and geophysical data, however, have shown that the complex is made up of different superimposed nappes that have undergone different tectonic and metamorphic histories; the total thickness of the nappes is <4 km (*17*). Petrological, geochemical, and radiometric studies (*18*) have shown that some units forming the Cabo Ortegal Complex (eclogite, Bacariza granulite, and Purrido amphibolite) originated in oceanic and island arc environments and then underwent high-pressure–high-temperature metamorphism around 490 and 420 million years ago. This evidence rules out the hypothesis that the whole complex originated in an in situ rift system.

The Herbeira ultramafic rocks, which crop out over an area of about 15 km^2, were initially described as homogeneous pargasite- and spinel-bearing harzburgite with minor pyroxenite bands and veins 0.5 to 5 cm thick (*11–14*). Van Calsteren (*15*) has suggested that these pyroxenite veins may represent partial melting products of the surrounding peridotite on the basis of their trace element compositions. Evidence that the host peridotite might be residual rocks left after melt extraction includes their CaO and Al_2O_3 contents, which range from 3.2 and 5.1 weight percent, respectively, in the amphibole-rich peridotite to 0.1 and 1.3

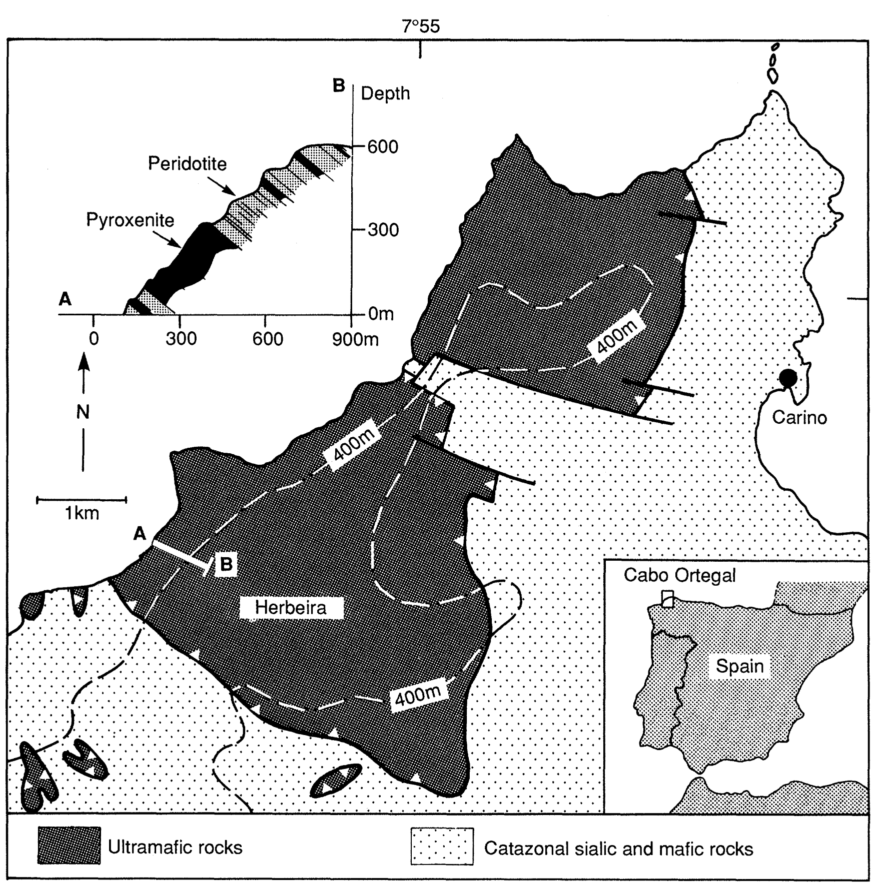

Fig. 1. Geological sketch map of the northern part of the Cabo Ortegal Complex (after *11*).

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in the more depleted amphibole-poor harzburgites (*13*). It is also evidenced by their phase chemistry: Mg/(Mg+Fe) ratios in olivine vary from 0.89 in the less depleted facies to 0.92 in the more depleted ones, and Cr/(Cr+Al) ratios in spinel vary from 0.12 to 0.78, respectively. Our studies have indicated that the main rock type of the Herbeira massif is actually pyroxenite, which occurs for the most part in a large band in foliated harzburgite.

In this large pyroxenite band, pyroxenite and peridotite layers alternate, with only one garnet-rich intercalation (Fig. 2). The pyroxenite band has a rather massive central part, about 300 m thick, dominantly formed by pyroxenite layers several tens of meters thick and dunite layers a few meters in thickness. The proportion of peridotite rapidly increases toward the base and top of the band where it locally makes up more than 80% of the rocks. The peridotite in the central pyroxenite-rich portion is dunite; at the base and top of the sheet it is harzburgite.

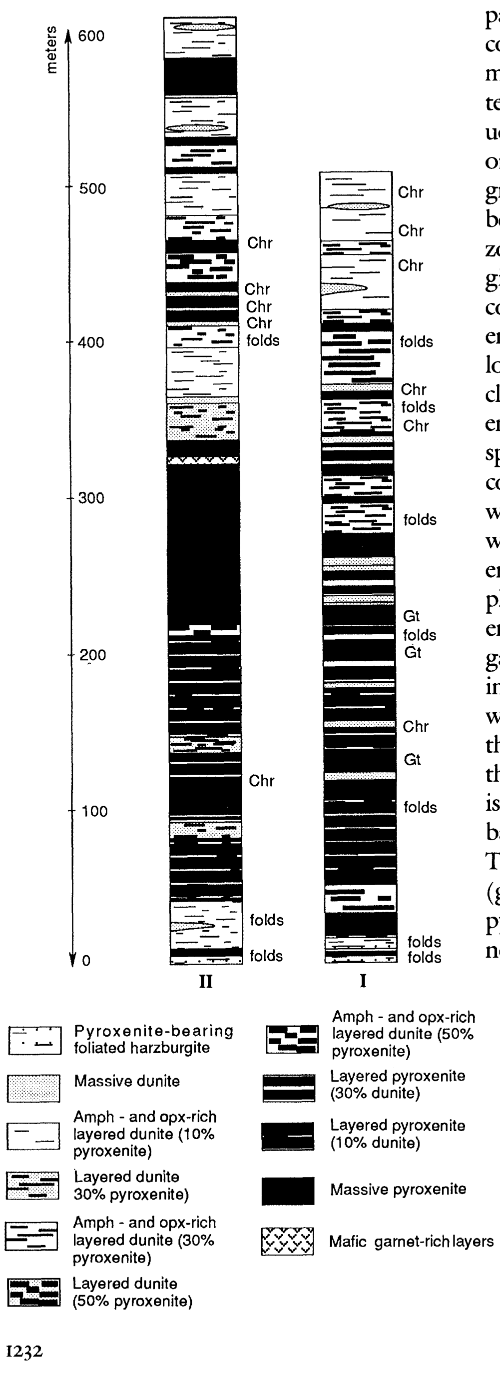

Fig. 2. Synthetic sections through the large-scale pyroxenite layer of the Herbeira massif (Cabo Ortegal). Chr, chromite enrichments; folds, highly deformed rocks showing intrafolial folds; Gt, garnet-rich layer; opx, orthopyroxene; amph, amphibole. Section I corresponds to section A-B on Fig. 1; Section II has been picked up about 500 m north of Section 1.

The pyroxenite comprises massive websterite (Fig. 3A), orthopyroxene-rich websterite, and clinopyroxenite in approximately equal amounts, and minor olivine websterite and orthopyroxenite. All the rocks are generally fresh. In some rocks, metamorphic amphibole has developed at the expense of pyroxene and some serpentine has formed after olivine, and more rarely iron and nickel sulfide phases occur as well as secondary magnetite. Massive websterite in the central part of the band is generally equant and coarse-grained (grain size between 2 and 5 mm). Some rocks have a poorly layered texture; the layering is marked by discontinuous thin orthopyroxenite bands. The orthopyroxene in the websterite displays grain-size variations that resemble graded-bedding structures. The websterite layers are zoned in some cases with olivine-rich margins and a fine-grained clinopyroxene-rich core. Coarse-grained rocks with orthopyroxene crystals more than 5 cm long occur locally. The websterite contains 70 to 90% clinopyroxene and 10 to 30% orthopyroxene and some trace interstitial olivine and spinel. Massive clinopyroxenite generally contains more than 5% orthopyroxene, which in the field makes its distinction from websterite difficult. The websterite, however, contains abundant large crystals of amphibole, which developed after clinopyroxene, and trace amounts of olivine and spinel; garnet also rarely occurs in these rocks as an interstitial phase. The orthopyroxene-rich websterite is layered and interbedded with the massive websterite in the central part of the pyroxenite band. The olivine websterite is scarce and mostly occurs as discontinuous bands in the dunite and harzburgite layers. These bands are generally fine-grained (grain size around 2 mm) and contain clinopyroxene, orthopyroxene, olivine, and spinel in variable amounts. Locally, chromite is enriched at the base of layers that resemble graded beds.

The dunite intercalated with the pyroxenite has a massive texture. The rocks may contain, as the olivine websterite, abundant, disseminated, large (2 to 3 mm across) chromite crystals at the base of the layers; the crystals become smaller and more euhedral upward. Some dunite locally contains small interstitial isolated orthopyroxene and minor amphibole in small discontinuous layers. These layers, in particular, occur in dunite associated with harzburgite in the lower and basal parts of the pyroxenite band.

The transition between the central pyroxenite-rich part of the band and the surrounding pyroxenite-poor harzburgitic parts is sharp and is marked by the presence of finely layered rocks in many places (Fig. 3B), particularly in the basal part of the large layer. The pyroxenite and peridotite layers generally display sharp and straight contacts (Fig. 3C) except for the scarce olivine websterite layers. The pyroxenite layers have variable thicknesses (2 mm to 3 m), and some layers show large lateral variations over short distances; others extend continuously for more than 100 m, however.

A garnet-rich layer, about 1.5 m thick, occurs near the top of the pyroxenite band in one section (Fig. 2). It lies parallel to the layering in the pyroxenite-dunite. It has a strongly banded structure with alternating garnet-, clinopyroxene- and amphibole-rich layers that are 5 to 20 cm thick; other layers are rich in amphibole or zoisite and amphibole. This garnet layer contains abundant spinel inclusions in garnet as well as some corundum. This is the only aluminum-rich layer we found in the pyroxenite section.

The finely layered rocks near the base and top of the pyroxenite band locally show tight isoclinal folds and boudinage structures. In places, these structures are in meter-sized shear zones cutting through the primary magmatic layering. The layering in this pyroxenite is subparallel to the main foliation in the surrounding peridotite. These relations suggest that some of the layering in the peridotite and pyroxenite is tectonic.

The peridotite that surrounds the large-scale pyroxenite layer contains pyroxenite bands that are generally less than a few tens of centimeters in thickness and that represent less than 10% of the rock. These pyroxenite layers display sharp contacts with the surrounding peridotite; they are not zoned and are similar in composition to pyroxenite in the large band. The layers are everywhere parallel to the foliation in the peridotite and are generally strongly deformed and boudin-

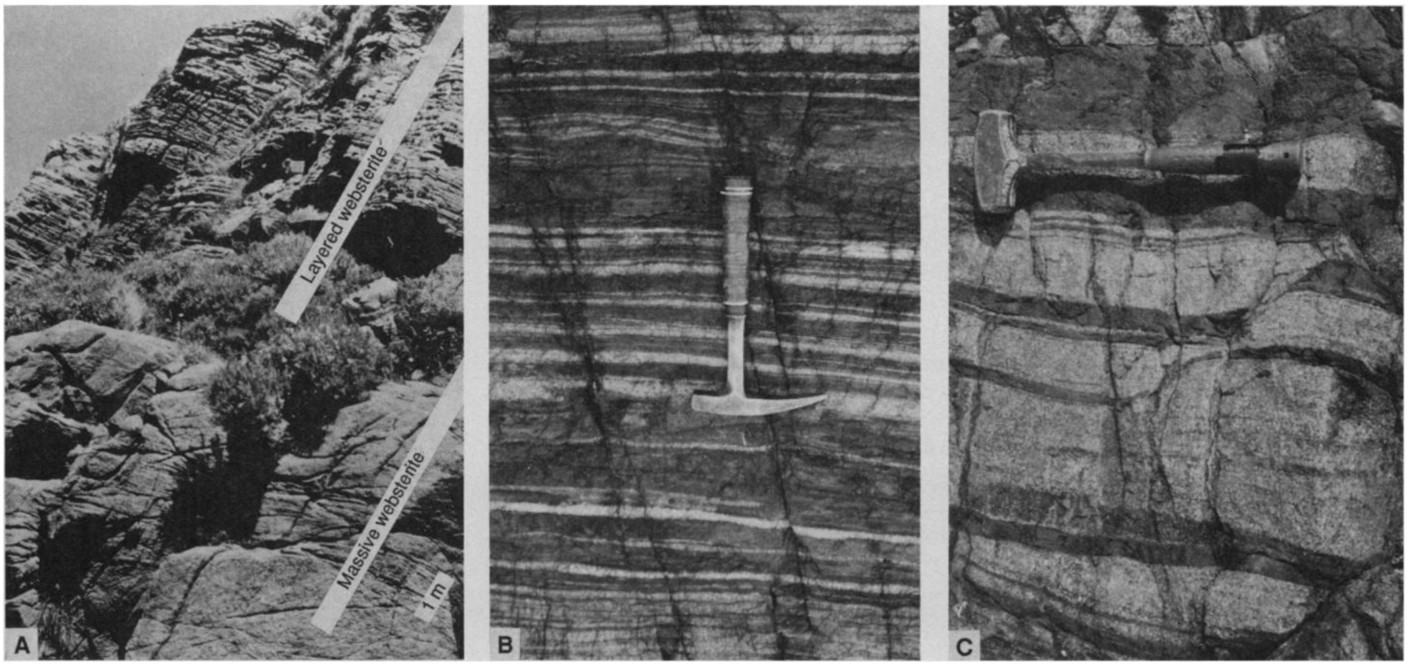

Fig. 3. (**A**) Thick layer of massive websterite between layered websterite in the central part of the pyroxenite; (**B**) finely layered pyroxenite (light layers) and dunite (dark layers) from the base of the pyroxenite sheet; (**C**) websterite (light) and dunite (dark) layers; note the sharp contacts between layers, the poorly layered nature of websterite, and the late normal faults cutting across the layers.

aged. Most likely, these thin pyroxenite layers resulted from shearing of thicker bands, as is likely for the layering in some of the finely layered rocks (Fig. 3B).

Locally, garnet-bearing dikes cut the pyroxenite layers and surrounding peridotite (Fig. 2). The dikes are generally thin (less than 10 cm across) and locally contain only garnet. Some are zoned, displaying thin clinopyroxene or amphibole rims and a garnet-rich core with minor phlogopite. These garnet dikes generally are oriented at high angles to the layering in the pyroxenite and to the foliation. They appear undeformed, except in the mylonites that separate the peridotite from the underlying granulites, where they are isoclinally folded, flattened, and boudinaged parallel to the mylonitic foliation. This relation indicates that the deformation in the pyroxenite and surrounding peridotite predates emplacement of the whole massif onto the underlying granulites.

Evidence that the pyroxenite might have had a magmatic origin includes (i) the local enrichment of euhedral chromite at the base of dunite and olivine-websterite bands; (ii) local variations in chromite modal contents, which constitute the only evidence for any kind of rhythmic layering, either in layers of the large pyroxenite band or at the band scale; and (iii) the presence of zoning in some of the pyroxenite layers. The origin of the large pyroxenite layer at Herbeira is uncertain. As there is little difference between the pyroxenite in the thin layers and those from the large-scale layer, the pyroxenite in the large layer may have formed through crystallization of melts produced by in situ partial melting of the associated peridotite, as has been proposed for the origin of the thin pyroxenite layers present in the peridotite (*15*). However, in order to account for the large volume of the pyroxenite in the pyroxenite band, large melt migration would most likely have to occur and, hence, the pyroxenite probably represents crystallization products of magmas in dikes intruded into the host mantle peridotite. However, this interpretation is not yet demonstrated. Whatever the origin of these pyroxenites, these rocks represent one of the best examples of a composite upper mantle and thus provide additional evidence that the upper mantle is heterogeneous.

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1. Pyroxenite is a rock composed of mostly (>90%) orthopyroxene and clinopyroxene. Typical upper mantle orthopyroxenite contains more than 90% orthopyroxene; clinopyroxenite more than 90% clinopyroxene. Websterite is a rock with more than 10% orthopyroxene and cloropyroxene. Peridotite contains lherzolite, harzburgite, and dunite. Dunite is an olivine-rich (>90%) peridotite.

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