Seismic anisotropy and compositionally induced velocity anomalies in the lithosphere above mantle plumes: a petrological and microstructural study of mantle xenoliths from French Polynesia

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Abstract

In addition to thermal erosion, plume/lithosphere interaction may induce significant changes in the lithosphere chemical composition. To constrain the extent of this process in an oceanic environment and its consequences on the lithosphere seismic properties, we investigated the relationship between petrological processes and microstructure in mantle xenoliths from different hotspots tracks in South Pacific Superswell region: the Austral-Cook, Society, and Marquesas islands in French Polynesia. Olivine forsterite contents in the studied spinel peridotites vary continuously from Fo91 to Fo83. Dunites and wehrlites display the lowest forsterite contents. Their microstructure and high Ni contents preclude a cumulate origin, suggesting that these rocks result from melt/rock reactions involving olivine precipitation and pyroxene dissolution. In addition, lherzolites and wehrlites display evidence of late crystallization of clinopyroxene, which may result from a near-solidus melt–freezing reaction. These data suggest that the lithosphere above a mantle plume undergoes a complex sequence of magmatic processes that significantly change its composition. These compositional changes, particularly iron enrichment in olivine, result in lower P- and S-waves velocities. Relative to normal lithospheric mantle, compositionally induced seismic anomalies may attain −2.2% for S-waves and −1% for P-waves. Smaller negative anomalies for P-waves are due to a higher sensitivity to modal composition. Conversely, crystal-preferred orientations (CPO) and seismic anisotropy are little affected by these processes. Lherzolites and harzburgites, independent from composition, show high-temperature porphyroclastic microstructures and strong olivine CPO. Dunites and wehrlites display annealing microstructures to which is associated a progressive dispersion of the olivine CPO. Very weak, almost random olivine CPO is nevertheless rare, suggesting...
that CPO destruction is restricted to domains of intense magma–rock interaction due to localized flow or accumulation of magmas.

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### 1. Introduction

Seismic tomography and anisotropy measurements are undoubtedly powerful tools to unravel the present-day thermal structure and deformation of the mantle. However, velocity heterogeneities may also reflect variations in composition within the mantle. Fast seismic velocity anomalies beneath cratonic domains, for instance, are usually interpreted as due to both a cold geotherm and a highly refractory lithospheric mantle [1]. Recent seismic tomography experiments show that the Ontong Java, Deccan, and Parana mesozoic large igneous provinces (LIP) are underlain by an abnormally slow upper mantle [2–5]. Unless related to present-day mantle plumes that coincidently impact below the three LIPs, these slow velocity domains cannot be interpreted as thermal anomalies, since the latter should have diffused since the Mesozoic. Moreover, the upper mantle below the Ontong Java plateau shows low seismic attenuation [6]. Together, these observations suggest that the slow seismic velocities below these basaltic provinces characterize an abnormal mantle root, formed by mantle rocks which composition has been modified by plume activity.

Seismic anisotropy in the upper mantle results essentially from orientation of olivine crystals during plastic deformation. In the high-temperature convecting mantle, olivine crystal-preferred orientations (CPO) is continuously modified and seismic anisotropy records present-day flow. On the other hand, the low temperatures and resulting high viscosities that prevail in the lithospheric mantle may freeze the olivine CPO over very long time spans. Indeed, shear wave splitting and Pn azimuthal anisotropy data in ancient continental domains (e.g., [7–9]) display a very good correlation with the major structures of collisional belts of Archean or Neoproterozoic age. Refraction experiments also show that fast P waves propagation directions in the uppermost mantle beneath oceans correlate with past seafloor spreading directions, suggesting that olivine CPO formed at the ridge may be frozen in the lithosphere for ≥100 My [10]. However, shear wave splitting data in some very young ocean islands, like Tahiti or La Réunion, detect no anisotropy [11,12]. This “apparent” isotropy has been interpreted as resulting from a “local” destruction of the olivine CPO in the lithosphere by the plume activity.

These observations suggest that plumes may induce long-lived changes in the upper mantle seismic properties. Possible candidates to produce seismic velocity and anisotropy variations in the mantle above a plume are changes in composition and texture of mantle rocks due to partial melting and melt–rock reactions. Direct analysis of mantle samples brought to the surface by plume-related magmas allows one to constrain the extent of these magmatic processes and their effect on seismic properties. In this study, which is part of the multidisciplinary Polynesian Lithosphere and Upper Mantle Experiment (PLUME) [13], we investigate the relationship between petrological processes, microstructure, and seismic properties in a series of mantle xenoliths from different hotspots tracks in South Pacific Superswell region: the Austral-Cook, Society, and Marquesas islands in French Polynesia. Two issues are essential to the interpretation of seismic data in terms of mantle structure and deformation patterns: How strongly do compositional heterogeneities produced by melt–rock interactions contribute to the velocity anomalies observed in seismic tomography? Do these processes modify the olivine CPO and hence the seismic anisotropy signature of the upper mantle?

### 2. Sampling

After optical analysis of a collection of 80 spinel-bearing mantle xenoliths, we selected 20 samples for
detailed microstructural investigation, electron microprobe analyses, and crystallographic orientation measurements: 4 lherzolites, 2 dunites and 2 wehrlites sampled within basanite boulders from the Fataua River valley in Tahiti (Society Islands), 4 harzburgites, 1 dunite and 1 wehrlite sampled in alkali-basalts outcropping on the western slopes of Mount Tanga in Rapa, and 1 lherzolite sampled within tephritic flows from the quarry of Mount Haramea in Tubuai (Austral Islands), 4 dunites from alkali-basalts from Ua Huka and 1 harzburgite from Fatu Hiva in the Marquesas archipelago. Ages of extraction vary from ~9.5 Ma in Tubuai [14] to 1 Ma in Tahiti [15]. These xenoliths range between 2 and 15 cm in diameter and are extremely fresh. All dunites and wehrlites as well as most lherzolites and harzburgites display sharp contacts with the enclosing basalt. Lherzolite samples from Tahiti display mm-scale reaction rims at the contact with the basalt, which were avoided in both textural and chemical analyses. Proportions of the various rock types (harzburgite, lherzolite, dunite, and wehrlite) in the suite selected for detailed analysis are representative of those observed for each sampling site in the total collection, except for Tahiti where dunites and wehrlites dominate.

3. Microstructures: deformation and magmatic reactions

3.1. Modal composition and microstructures

The studied lherzolites and harzburgites are characterized by relatively fertile compositions, with clinopyroxene contents ranging from 4–5 to 12 vol.% Only two samples, harzburgite RPA18A and lherzolite THTFA1A, display modal compositions consistent with those predicted by partial melting models (Fig. 1). The remaining are enriched in clinopyroxene or in olivine, the strongest enrichments being observed in Tahiti lherzolites and in the Marquesas harzburgite FTH101A. Most lherzolites and harzburgites exhibit coarse-grained porphyroclastic microstructures characteristic of deformation by dislocation creep under high-temperature, low-stress conditions (T>1100 °C). Foliation and lineation are usually marked by elongation of olivine porphyroclasts up to 5 mm long with curvilinear grain boundaries and well-developed and widely spaced (100) subgrain boundaries (Fig. 2a). Interpenetrating olivine–olivine grain boundaries indicate active grain boundary migration that, in some samples (e.g., RPA12), gives rise to cm-scale olivine grains (abnormal grain growth).

In a few samples (e.g., RPA18A), elongated lens-shaped orthopyroxene crystals (Fig. 2a) mark the deformation fabric. However, orthopyroxene is mostly present as irregularly shaped crystals (0.5 to 4 mm), which either display no shape-preferred orientation or are elongated at high angle to the olivine fabric (THTFA1A and THTFA4A, Fig. 2b). Orthopyroxene (opx) often displays corroded grain shapes, with corrosion embayments filled by olivine (Fig. 2d) or clinopyroxene (Fig. 2e), and secondary crystallization
of clinopyroxene, olivine, or spinel along kinks or fractures. Corrosion may explain the “abnormal” orthopyroxene shape-preferred orientation observed in the Tahiti lherzolite suite.

Clinopyroxene (cpx) generally occurs as isolated grains or monophase aggregates with a clear interstitial habit (Figs. 2f and 3) or within corrosion embayments of orthopyroxene and olivine grains (Fig. 2e–f). Typical opx–cpx–spinel aggregates are less common. Tahiti lherzolites also show 1–2 mm wide cpx-rich veinlets, clearly truncated by the basalt at the xenolith margin (Fig. 3). These observations suggest an origin by secondary crystallization for, at least, part of the clinopyroxenes in the studied peridotites. Together with orthopyroxene corrosion, this could result in the high cpx/opx ratios that distinguish Tahiti lherzolites THTFA4A and THTFA5 (Fig. 1b).
Surprisingly, spinels do not mark the deformation fabric, not even in peridotites that display a well-developed olivine shape-preferred orientation. They occur either as vermicular grains within olivine aggregates (Fig. 2b) or, more often, as interstitial grains (isolated or in association with clinopyroxene), which cusp shapes suggest a secondary origin (Fig. 3). Locally, symplectitic intergrowths of spinel and clinopyroxene are also observed.

Two samples, lherzolite TB110D and harzburgite RPA1A, are distinguished by a bimodal grain size distribution characterized by coexistence of olivine and orthopyroxene porphyroclasts with a fine-grained matrix (~0.5 mm) composed by polygonal olivine and orthopyroxene grains, as well as interstitial clinopyroxene and spinel. This matrix forms either cm-scale bands roughly parallel to the elongation of orthopyroxene porphyroclasts (TB110D) or discontinuous mm-scale seams that crosscut the entire xenolith in two roughly orthogonal directions (RPA1B, Fig. 2c). Olivine porphyroclasts either display widely spaced subgrains and sutured boundaries, indicative of active grain boundary migration, or display polygonal shapes. Matrix grains usually do not show any strain features. Orthopyroxene porphyroclasts often exhibit reaction rims (Fig. 2e) or secondary crystallization of olivine, spinel or clinopyroxene along kinks or fractures. A similar microstructure is also observed in a cm-scale band in harzburgite FTH101A, which otherwise displays a typical high-temperature porphyroclastic microstructure. The bimodal grain size distribution suggests deformation under higher stress (lower temperature?) conditions, in which dynamic recrystallization lead to significant grain size refinement. However, only lherzolite TB110D shows both a shape-preferred orientation and kinks in orthopyroxene porphyroclasts supporting this interpretation.

In contrast to lherzolites and harzburgites, dunites and wehrlites do not display any clear deformation microstructures; shape-preferred orientations marking a macroscopic foliation or lineation are never observed. Both dunites and wehrlites are equigranular and show microstructures that indicate that static recrystallization processes and, in particular, grain boundary migration were very active. These microstructures range from highly lobated, interpenetrating olivine grain boundaries, observed in most dunites from Austral and Society islands (Fig. 4a), to polygonal textures, characterized by straight grain boundaries meeting at 120° (Fig. 4b), which are typical of dunites from Marquesas islands and of wehrlites. Despite the important grain boundary migration, grain sizes are usually smaller than in the lherzolites. Olivine crystals are generally devoid of internal deformation features. However, a few porphyroclasts still retain clear subgrain boundaries (Fig. 4a), suggesting an early deformation incompletely erased by static recrystallization. Spinel occurs as small polygonal grains (~0.5 mm) at triple junctions or as inclusions in olivine, as a result of the active migration of olivine grain boundaries. Most dunites display small amounts (<5%) of interstitial clinopyroxene, but orthopyroxene is never observed. In the wehrlites, clinopyroxene content ranges from 31 to 37 vol.%. It is either interstitial, forming semi-continuous seams (Fig. 4c), or poikiloblastic, enclosing corroded olivine grains (Fig. 4d). This suggests that the wehrlites formed at the expense of dunites by secondary crystallization of clinopyroxene. In addition, the annealing microstructure, which is better developed in the Marquesas dunites and wehrlites, suggests that these rocks have been submitted to high temperatures, probably under static conditions.
3.2. Crystal-preferred orientations

Olivine and pyroxenes crystallographic orientations (CPO) were determined by indexing of electron back-scattered diffraction (EBSD) patterns. All samples were analyzed manually (i.e., indexing of every crystal was verified by the operator) to avoid errors due to the pseudo-hexagonal symmetry of olivine in the [100] direction. Measurements were done in a grain by grain basis along 3-mm-spacing profiles parallel to the long axis of the thin section.

Lherzolites and harzburgites, independently from composition or microstructure, show very strong and homogeneous olivine CPO, characterized by a strong alignment of [100] axes close to the lineation (marked by the olivine shape-preferred orientation) and a girdle distribution of [010] and [001] normal to it, with weaker maxima normal and parallel to the foliation, respectively (Fig. 5). This olivine CPO suggests deformation by dislocation creep with dominant activation of the high-temperature (010)[100] and (001)[100] slip systems. Lherzolite TB110D is the single exception to this pattern. It displays a much weaker olivine CPO characterized by a concentration of [100] axes parallel to the lineation and of [001] axes normal to the foliation, which, in this sample, are clearly marked by the elongation of orthopyroxene porphyroclasts and by the preferred orientation of fine-grained domains. Coarse- and fine-grained domains display similar olivine CPO. This suggests that the bimodal texture and the weak CPO result from deformation by dislocation creep under high-stress conditions, in which dynamic recrystallization lead to significant grain size refinement.

Orthopyroxene CPO are coherent with the olivine ones, but much weaker (see online supplementary Fig. 1). [001] axes concentrate close to the lineation and [100] and [010] are distributed in a girdle normal to it, suggesting activation of \{h0\}\{001\} systems. Yet, in most samples, there is a small obliquity ($\sim 15^\circ$) between the olivine and orthopyroxene CPOs. This suggests that olivine and orthopyroxene underwent...
the same deformation, but harder orthopyroxene grains accommodated smaller strains than olivine ones. Clinopyroxene usually displays almost random CPO, except in harzburgite FTH101A that is characterized by parallelism of orthopyroxene and clinopyroxene CPOs and in lherzolite TB110D, which displays a clinopyroxene CPO oblique to both the olivine and orthopyroxene ones.

Dunites and wehrlites display weak olivine CPO, which are often characterized by higher concentrations of the [010] axes relative to [100] and [001] (Fig. 6). CPO intensity is related to microstructure. Dunites with lobate grain boundaries retain an olivine CPO similar to, although much weaker, than those observed in the lherzolites and harzburgites. Polygonal dunites and wehrlites display even weaker, almost isotropic, olivine CPO. This suggests that static recrystallization contributed to the dispersion of the olivine CPO. Clinopyroxene CPO in wehrlites also relates to the microstructure (Background Dataset Fig. 2). Poikilitic diopside in wehrlite RPA9 displays an almost random orientation, whereas interstitial diopside in wehrlite THTFA5A/3A displays a weak, but well-organized CPO in good agreement with the olivine one, suggesting a common deformation.

4. Mineral chemistry: evidence for extensive melt/rock interaction

Olivine in lherzolites and harzburgites is characterized by a wide range of compositions with Mg# (Mg# = Mg/(Mg+Fe)) ranging from 86 to 91 and Ni contents from 2400 to 3400 ppm (Fig. 7a). These variations are correlated to the olivine content; harzburgites usually display higher Mg# as expected for partial melting. Peridotites with bimodal textures display variations in olivine composition at the sample scale: olivine from fine-grained bands in harzburgites RPA1B and FTH101A displays lower Ni contents and Mg# than the porphyroclasts (Fig. 7a). Fe-rich olivine compositions of lherzolites overlap with those of the dunites and wehrlites (Mg# = 83–86 and Ni = 1600–2900 ppm). Core–rim compositional gradients are restricted to one sample, lherzolite THTFA4A, which shows a clear decrease in Mg# and Ni content from core (Mg# = 89; Ni = 3000 ppm) to rim (Mg# = 83–87; Ni = 1700–2400 ppm).

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**Fig. 5. Olivine crystal-preferred orientations (CPO) in the lherzolites and harzburgites. Lower hemisphere equal-area projection, n measurements, contours at 1 multiple of a uniform distribution intervals. Full line marks the orientation of the foliation (XY plane); lineation (X direction) is horizontal. Mean forsterite content (Mg#) of olivine in each sample is also indicated.**
Orthopyroxene (opx) is enstatite with Mg# ranging from 87 to 91 and variable TiO$_2$ contents (0.02–0.19 wt.%). Clinopyroxene is Cr-rich diopside (Cr$_2$O$_3$=0.7–1.1 wt.%) with Mg# ranging from 84 to 93, the lowest Mg# (84–87) values being measured in wehrlites. Clinopyroxenes display also variable TiO$_2$ contents (0.02–0.94 wt.% in lherzolites and harzburgites, 0.83–1.33 wt.% in wehrlites). In contrast to olivine, pyroxenes are homogeneous at both grain and sample scales except for wehrlite RPA9, whose small interstitial grains display the lowest Mg# (83) and Cr$_2$O$_3$ values (0.46 wt.%) and highest TiO$_2$ content (2.2 wt.% observed in the studied xenolith suite (Fig. 7b–c).

Al$_2$O$_3$, Na$_2$O and CaO contents in lherzolites and harzburgites distinguish the different archipelagoes. High Al$_2$O$_3$ contents (5–5.2 wt.% in opx and 6.2–6.85 wt.% in cpx) in Tahiti lherzolites stand out against the low Al$_2$O$_3$ values of the Australs and Marquesas peridotites (2.1–3.1 wt.% in opx and 2.5–4.2 wt.% in cpx). The lower CaO and higher Na$_2$O content of clinopyroxenes in Tahiti lherzolites suggest that these peridotites were equilibrated at higher pressures than the other studied xenoliths. Higher Al$^{IV}$/Al$^{VI}$ ratios in clinopyroxenes from wehrlites (2.5–4.5) relative to Rapa harzburgites (1.5–2.9) and to Tahiti lherzolites (0.8–1.2) suggest that wehrlites were equilibrated at lower pressures. Thermometers based on Al–Ca distribution in pyroxenes indicate also higher equilibration temperatures for Tahiti samples (1040–1080 °C [16] and 1010–1035 °C [17]) than Australs peridotites (890–950 °C [16], 910–980 °C [17]).

Spinel show a wide range of compositions (Fig. 7d) consistent with the variable degree of fertility of the studied peridotites. Variations in spinel composition also distinguish the different archipelagoes. Tahiti lherzolites display the lowest Cr# (15–26) and highest Mg# (64–72), while Marquesas harzburgite and dunites display higher Cr# (50–57) and lower Mg# (30–45). The most striking feature in the studied spinels is the strong variation in TiO$_2$ content (0.04–9.45 wt.%). The most enriched sample is Marquesas harzburgite FTH101A and the high Mg# Rapa

Fig. 6. Olivine crystal–preferred orientations in the dunites and wehrlites. Lower hemisphere equal-area projection, n measurements, contours at 1 multiple of a uniform distribution intervals. No shape–preferred orientation marking a foliation or lineation is observed in these samples.
harzburgites display the lowest values. The studied xenoliths (with exception of FTH101A) show an inverse correlation between TiO$_2$ in spinel and olivine Mg#, the higher spinel TiO$_2$ content and lower olivine Mg# being found in dunites and wehrlites (Fig. 7d).

Dunites with Fe-rich olivines are common in oceanic environments (e.g., Hawaii [19], French Polynesia, and La Réunion [20]). Because of (1) their systematic association with wehrlites and (2) their high Fe-content, they were first interpreted as cumulates [19]. However, olivines in these dunites and wehrlites differ from those crystallizing from a basalt by their high Ni content at a given Mg# (Fig. 7a). Basalts in equilibrium with peridotites at depth become increasingly orthopyroxene-undersaturated as pressure decreases [21]. Berger and Vannier [20] and Kelemen et al. [21] proposed therefore that dunites formed at low pressures (<1.5 GPa) by reaction between peridotites and an olivine-saturated basaltic melt leading to dissolution of pyroxene and precipitation of olivine. Microstructural evidence of early high-temperature deformation followed by static recrystallization (Fig. 4a) also favors a reactional origin for the studied dunites.

The interstitial habit, high Al$^{IV}$/Al$^{VI}$ ratios, and high TiO$_2$ content of clinopyroxene in wehrlites suggests that it is the product of a late, low-pressure crystallization of a percolating basaltic melt within the dunites. Similar impregnation features are observed at the Moho Transition Zone (MTZ) in ophiolites [22–24]. Variations in clinopyroxene composition may be related to changes in melt composition, the higher Ti

Fig. 7. Olivine Ni content (a), clinopyroxene Mg# (b), orthopyroxene Mg# (c), and spinel TiO$_2$ content (d) as a function of the olivine Mg# in the studied xenolith suite. Symbols are shown in inset. Variations in olivine composition within samples are distinguished by L (large grains) and S (small grains) when dependent on grain size, and by (c) and (r) for core to rim variations. Interstitial cpx compositions in RPA9 are highlighted by (i). For comparison, a compilation of olivine compositions previously measured in Society and Austral xenoliths is shown in (a) [20,49–53]. Evolution of Ni content and Mg# in olivine during fractional crystallization in a closed system is calculated by subtracting iteratively (in increments of 0.1 wt.%) olivine in equilibrium with the evolving melt using olivine/liquid partition coefficient values from [54] for FeO/MgO and from [55] for Ni. Initial melt composition is Mg#=74 (after [56]) and Ni=360 ppm. Diamonds mark crystallized fractions by 1% increments, numbers in square brackets label 5% increments. Black diamonds distinguish the fractional crystallization trend from the equilibrium crystallization trend (white diamonds).
interstitial clinopyroxene in RPA9 resulting from late crystallization of a more differentiated melt. Dunites and wehrlites thus formed by melt/rock reactions involving olivine precipitation, followed by melt consumption through clinopyroxene precipitation.

Fe-rich compositions of harzburgites and lherzolites, as well as Ti-enrichment in pyroxenes and spinel (Fig. 7) and low Cr$_2$O$_3$ contents in clinopyroxene, suggest that these rocks also underwent chemical reequilibration, at depth, with percolating Fe–Ti-rich melts. This interaction is more developed in Tahiti lherzolites and in the fine-grained domains of RPA1B and FTH101A. Thus, melt–rock interaction probably played an important role in the formation of the bimodal texture in these samples. Although Fe–Mg interdiffusion rates in olivine are fast [18], homogeneous Mg# at cm-scale in lherzolites and harzburgites imply melt–rock interaction times >10$^4$ years, which suggest that Fe-enrichment is not associated with fast magma flow through dikes. Incomplete melt–rock Fe–Mg reequilibration, as evidenced by core–rim compositional gradients, is recorded only in sample THTFA1A and may be related to xenolith extraction. The high cpx/opx ratios, the corrosion features in orthopyroxene, and the often interstitial habit of clinopyroxene suggest that, in the lherzolites, reaction with basaltic melts also modified modal compositions through precipitation of clinopyroxene. Secondary crystallization of clinopyroxene has been described in orogenic and ophiolitic massifs and interpreted as a melt–freezing reaction at the lithosphere/asthenosphere interface [25]. In the studied xenoliths, secondary crystallization of clinopyroxene is related to the equilibration temperature, the most affected being the high-temperature Tahiti lherzolites.

5. Seismic properties of the lithosphere above a mantle plume

To constrain the effect of the compositional and textural changes induced by melt–rock interactions on the mantle seismic properties, the three-dimensional distributions of seismic velocities in each sample were estimated by averaging the individual grain elastic constants tensors as a function of the crystallographic orientations and modal composition [26]. In the present calculations, we used single-crystal elastic constants tensors of olivine, enstatite, and diopside at ambient conditions [27–29] and Voigt–Reuss–Hill averages. In addition, the dependence of olivine elastic constants and density on the forsterite content [30] was explicitly taken into account.

5.1. Seismic anisotropy

Lherzolites and harzburgites display compressional (P) waves velocity distributions and shear (S) waves anisotropy patterns (Fig. 8) typical of upper mantle rocks deformed under high-temperature conditions. P-waves are the fastest when propagating parallel to the lineation (maximum concentration of olivine [100] axes) and the slowest when propagating normal to the foliation (parallel to the maximum concentration of olivine [010] axes). Except for lherzolite TB110D, all lherzolites and harzburgites are highly anisotropic. P-waves azimuthal anisotropy is 9–11% and S-waves polarization anisotropy may attain 5–7%. The highest anisotropies are displayed by the Mg-rich harzburgite RPA18A, which displays the least modified chemical and mineralogical composition (Fig. 9). Fast S-waves are polarized parallel to the maximum concentration of olivine [100] axes, i.e., the lineation. Polarization anisotropy is minimum for S-waves propagating at low angles to the lineation and maximum for those propagating at high angles to the lineation.

Dunites and wehrlites display weak anisotropies for both P- and S-waves. Anisotropy intensity does not depend on olivine composition (Fig. 9). There is, however, a relation between anisotropy and microstructure (Fig. 10). The lowest anisotropies are displayed by dunites and wehrlites with well-developed polygonal textures. Although weaker, P-waves velocity distributions and S-waves anisotropy patterns of dunites and wehrlites are similar to those displayed by the lherzolites. However, since these rocks do not show any shape-preferred orientation marking a foliation or a lineation, seismic anisotropy may only be related to flow in the upper mantle by assuming that olivine [100] and [010] axes align, respectively, parallel to the flow direction and normal to the flow plane, as usually in peridotites deformed under high-temperature conditions.

We interpret the reduction in seismic anisotropy in the dunites and wehrlites relative to lherzolites and
Harzburgites as a result of the dispersion of the olivine CPO due to crystallization of non-oriented olivine neoblasts during dunite-forming melt–rock reactions. Static recrystallization may have contributed to the dispersion of the olivine CPO and, hence, to the decrease in anisotropy, by favoring growth of the new, undeformed neoblasts at the expenses of the old grains. Thus, melt–rock reactions may locally erase the seismic anisotropy signature of the lithospheric mantle. They may also modify the seismic velocities.

Fig. 8. Modeled three-dimensional compressional waves velocity and shear wave anisotropy (intensity and polarization direction of the fast wave) distributions for lherzolites and harzburgites. Voigt–Reuss–Hill averages calculated from crystallographic orientation data and elastic constants tensors for olivine, enstatite, and diopside at ambient conditions [27–29]. Modal compositions used in the calculations, as well as the forsterite content of olivine are indicated on the right of each plot. The variation of elastic constants and density of olivine associated with changes in forsterite content [30] was explicitly taken into account in the calculation. Lower hemisphere equal-area projections, contours for P-waves velocities and S-wave anisotropy at 0.1 km/s and 1% intervals, respectively. Full line marks the foliation (XY plane); lineation (X direction) is horizontal.

Fig. 9. P-wave (a) and maximum S-wave (b) anisotropies as a function of the mean forsterite content of olivine in each sample. Symbols as in Fig. 7.
5.2. Compositional seismic velocity anomalies

Analysis of the variation of isotropic $Q_P$- and $Q_S$-waves velocities as a function of the mean olivine forsterite content in each sample (Fig. 11) shows that...
S- and P-waves velocities decrease with Fe-enrichment in olivine. However, P-wave velocities are also highly sensitive to the modal composition of mantle rocks; a decrease in enstatite content from 25% to 0% (i.e., the transformation of a harzburgite in a dunite by progressive dissolution of pyroxenes and crystallization of olivine) results in an increase of P-waves velocities equivalent to a variation in olivine composition from Fo91 to Fo85. As a consequence, dunites display “isotropic” P-wave velocities similar or slightly higher than the ones shown by the lherzolites. Lower P-wave, but similar S-wave velocities in wehrlites relatively to dunites with similar olivine Mg# also point to a stronger sensitivity of P-waves to modal composition.

If we consider harzburgite RPA18A, which displays the least modified mineral compositions and strongest CPO, as representative of the “normal” oceanic lithospheric mantle, S-wave negative velocity anomalies display a clear anticorrelation with olivine forsterite content (Fig. 12). Maximum anomalies (−2.25%) are associated with the wehrlites. However, even the small compositional changes observed in the lherzolites do result in significant negative seismic anomalies (up to −1.25%) for shear waves. P-wave velocity anomalies show a more complicated pattern, since the effects of olivine forsterite content and modal composition may either add or subtract depending on the physico-chemical conditions of the magma–rock interaction. Maximum negative anomalies (−1%) are displayed by Fe-rich wehrlite THTFA3A and pyroxene-rich lherzolite THTFA1A. Thus, Fe-enrichment in olivine and pyroxene crystallization do result in a decrease of P-wave velocities, as shown by the dunites and wehrlites and also, although less clearly, by the lherzolites and harzburgites. However, if Fe-enrichment in olivine is accompanied by dunite-forming reactions, i.e., dissolution of pyroxenes and crystallization of olivine, the final result is most often an increase in P-wave velocities. Influence of enstatite content on P-wave velocities should nevertheless decrease with increasing depth, since bulk modulus pressure-derivatives are higher in enstatite than in olivine, leading to similar P-wave velocities in both minerals at ~200 km depth [31].

6. Discussion

The studied xenolith suite samples an oceanic lithosphere modified, to variable extent, by melt percolation associated with mantle plumes. Interaction with basaltic melts results in changes in both the chemical (mainly Fe-enrichment) and the mineralogical compositions of mantle. Clinopyroxene-rich lherzolites are produced by a near-solidus melt–freezing reaction occurring at the boundary of a partial melting domain. This reaction preserves the pre-existing deformation microstructures and CPO. On the other hand, as they infiltrate the lithosphere, melts formed at depth equilibrate with peridotites by dissolving orthopyroxene. They become, as a result, mineralogically non-reactive. However, Fe–Mg exchanges (as well as trace element exchanges, such Ti in spinel and pyroxenes) between melt and minerals may still occur as long as percolation continues. Complete dunitification takes place only at low pressure, when the melt becomes olivine saturated, and for high melt/rock ratios. Crystallization of new, non-oriented olivine neoblasts during these dunite-forming reactions leads to dispersion of
pre-existing olivine CPO. Late melt crystallization in dunites produces wehrlites. Predominance of olivine or pyroxene crystallizing reactions, as well as their extent, depends both on the composition and volume of the magma and on pressure and temperature conditions [25].

6.1. Seismic signature of melt–percolation processes in the mantle

Although reactions change their composition, crystallographic-preferred orientations and, hence, seismic anisotropy of lherzolites and harzburgites are little affected by the percolation of magmas. Most harzburgites and lherzolites display coarse porphyroclastic microstructures and strong olivine CPO, characteristic of deformation under high-temperature, low-stress, asthenospheric conditions, which were frozen in the lithospheric mantle by progressive cooling of the plate [32]. Weakening of the olivine CPO leading to almost isotropic properties is only observed in dunites and wehrlites, suggesting that it is restricted to domains of intense magma–rock interaction due to enhanced percolation or to accumulation of magmas.

On the other hand, the iron-enrichment results in an increase in density and a decrease in seismic velocities for both P and S-waves. P-wave velocities are also highly sensitive to variations in pyroxene content, in particular enstatite. Therefore, olivine-crystallization reactions may result in higher P-wave velocities, while pyroxene crystallization decreases them. Relative to normal mantle, seismic anomalies associated with a Fe-rich wehrlite may attain −0.75% and −2.25% for compressional and shear waves, respectively. This S-wave negative seismic anomaly, in particular, is equivalent to the one produced by a 200–100-K temperature anomaly in the mantle, the lower values corresponding to more effective viscoelastic relaxation processes in the upper mantle due to higher temperature, lower grain sizes, and lower frequencies [33,34]. Even the smaller compositional changes observed in the lherzolites produce significant seismic anomalies: up to −1% and −1.25% for P- and S-waves, respectively.

Melt–rock interactions above mantle plumes can both weaken seismic anisotropy and modify seismic velocities. The resulting seismic anomalies may be preserved in the lithospheric mantle for very long time spans. Yet, before the present observations are used to interpret seismic tomography or seismic anisotropy data, some fundamental questions concerning the extent and spatial distribution of these percolation-induced compositional and textural variations should be addressed. What is the spatial distribution of the dunites and wehrlites in the lithospheric mantle? Do they correspond to a large-scale modification of the uppermost lithospheric mantle above a mantle plume or are they reactional rocks produced by a localized magma flow in the lithospheric mantle? Do the compositional changes observed in the lherzolites result from a diffuse percolation that may affect the large domains of the lithosphere above the plume?

The spatial distribution and structural relationships between different mantle lithologies (lherzolites, harzburgites, and dunites) may be inferred from the study of peridotite massifs representative of tectonically uplifted oceanic (ophiolites) and continental (orogenic peridotites) mantle sections. These studies highlight that melt transfer and melt–rock interactions take place by mechanisms as varied as melt flow in lithospheric centimetric to metric-scale vein conduits and wall–rock reactions [35], melt extraction from mantle sources via channeled porous flow [36], or propagation of km-scale melting and percolation fronts associated with thermal erosion of lithospheric mantle [37].

Peridotite massifs are generally characterized by a predominance of lherzolites or harzburgites. Dunites are observed as irregular lenses or, most commonly, tabular bodies, a few tens of centimeters to a few hundreds meters thick. Within ophiolites, dunite bodies are particularly common in the uppermost mantle section, where they are interlayered with gabbros and websterites [22]. Predominance of Fe-rich dunites, wehrlites, and websterites is observed only in km-scale ultramafic massifs interpreted as representative of the shallow mantle beneath magmatic arcs, such as the Urals and Kohistan ultramafics [25]. These observations suggest that formation of dunites is essentially related to focused melt flow, either in veins or via channeled porous flow, or to melt accumulations at permeability barriers such as the Moho discontinuity or the base of the lithosphere [25]. Thus, we regard as unlikely the development of large-scale (few tens of kilometers) dunite bodies in the
The present data suggests that, as far as it only implies thermal and petrological processes, plume–lithosphere interaction preserves the lithospheric seismic anisotropy rather than erases it. This prediction is in good agreement with shear wave splitting measurements in plume-related islands in the Pacific, Atlantic, and Indian oceans that usually show fast-shear waves polarized at small angles to the absolute plate motion in the hotspot reference frame and delay times of 1 to 1.5 s [11,12,39–41].

Recent geochemical and petrophysical studies in the Ronda peridotite massif (southern Spain) also show that partial melting and melt transport associated with an “asthenospherization” process may change the microstructure and the chemical composition of lithospheric mantle [37], but preserve the pre-existing olivine CPO and seismic anisotropy [42]. Thus, thermo-chemical erosion of the lithospheric mantle may produce contrasting signatures for seismic velocities and anisotropy. The hot “asthenospherized” lithosphere will be imaged by seismic tomography as a shallow low velocity anomaly suggesting a thinned lithosphere, but seismic anisotropy measurements will reflect the pre-existing lithospheric structure and hence detect no variation between thinned and “normal” domains [42]. Such an apparent paradox between seismic tomography and anisotropy data sets characterizes for instance the Yellowstone hotspot wake in the western US [43].

The apparent isotropy observed in Tahiti, Azores, and La Réunion [11,41] remains an unsolved question. Lherzolite xenoliths from Tahiti display indeed very strong olivine CPO. Absence of shear wave splitting may yet result from non-coherent olivine CPO at the length scales sampled by SKS waves (50 km), from a vertical alignment of olivine [100] axes, i.e., from vertical flow directions in the lithosphere and asthenosphere (Fig. 8), or from a destructive interference between the lithospheric and asthenospheric contributions. None of these hypotheses is fully satisfactory. An upwelling plume may produce vertical flow or small-scale variations in flow direction in the asthenosphere, but the lithosphere should retain its olivine CPO unless it is mechanically eroded. Moreover, seismic anisotropy data in most oceanic island stations are better explained by olivine CPO developed in response to a constant velocity gradient between the plate and the deep mantle, leading to similar orientations of the lithospheric and asthenospheric anisotropies [32].
imply a temperature anomaly $\geq 250$ K [33,34]. Such a
temperature anomaly would induce both partial melting and high attenuation and neither of these phenomena is observed below Ontong Java today [6].

The close spatial correlation between 1% and 2% slow velocity anomalies within the lithospheric mantle and the location of Paleogene volcanics and magmatic underplating (part of the North Atlantic igneous province) observed in a recent seismic tomography study on the British Isles [44] suggests that slow velocities may result from compositional changes in the lithospheric mantle composition similar to those described in this study. Finally, the lower than average seismic velocities observed in the mantle beneath the Bushveld province in the Kapvaal craton also suggest local Fe-enrichment of the cratonic lithosphere by this 2.05-Ga-old magmatic event [45].

7. Conclusion

The microstructural and petrological analysis of a series of mantle xenoliths from different archipelagoes within the South Pacific Superswell suggests that the oceanic lithosphere above a mantle plume undergoes a complex sequence of magmatic processes that induces significant changes in its chemical and modal composition. These compositional changes, particularly secondary crystallization of pyroxenes and iron enrichment in olivine, result in lower seismic velocities for P- and S-waves. Relative to normal lithospheric mantle, compositionally induced seismic anomalies may attain $-2.2\%$ for S-waves and $-1\%$ for P-waves. Melt–freezing reactions and iron-enrichment of olivine associated with diffuse flow of magmas in the lithospheric mantle may thus be good candidates to form large-scale compositional anomalies in the upper mantle.

On the other hand, crystal-preferred orientations (CPO) and hence seismic anisotropy are little affected by these processes. Lherzolites and harzburgites, independently from Fe-content, show high-temperature porphyroclastic microstructures and strong olivine CPO. Dunites and wehrlites display annealing microstructures to which is associated a progressive weakening of the olivine CPO. However, very weak, almost random olivine CPO is rare, suggesting that CPO destruction is restricted to domains of intense magma–rock interaction due to localized flow or accumulation of magmas.

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Appendix A. Supplementary material


References


