Constraints on the seismic properties of the middle and lower continental crust

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Abstract: For the past two decades geodetic measurements have quantified surface displacement fields for the continents, illustrating a general complexity. However, the linkage of geodetically defined displacements in the continents to mantle flow and plate tectonics demands understanding of ductile deformations in the middle and lower continental crust. Advances in seismic anisotropy studies are beginning to allow such work, especially in the Himalaya and Tibet, using passive seismological experiments (e.g. teleseismic receiver functions and records from local earthquakes). Although there is general agreement that measured seismic anisotropy in the middle and lower crust reflects bulk mineral alignment (i.e. crystallographic preferred orientation, CPO), there is a need to calibrate the seismic response to deformation structures and their kinematics. Here, we take on this challenge by deducing the seismic properties of typical mid- and lower-crustal rocks that have experienced ductile deformation through quantitative measures of CPO in samples from appropriate outcrops. The effective database of CPO and hence seismic properties can be expanded by a modelling approach that utilizes ‘rock recipes’ derived from the as-measured individual mineral CPOs combined in varying modal proportions. In addition, different deformation fabrics may be diagnostic of specific deformation kinematics that can serve to constrain interpretations of seismic anisotropy data from the continental crust. Thus, the use of ‘fabric recipes’ based on subsets of individual rock fabric CPO allows the effect of different fabrics (e.g. foliations) to be investigated and interpreted from their seismic response. A key issue is the possible discrimination between continental crustal deformation models with strongly localized simple-shear (ductile fault) fabrics from more distributed (‘pure-shear’) crustal flow. The results of our combined rock and fabric-recipe modelling suggest that the seismic properties of the middle and lower crust depend on deformation state and orientation as well as composition, while reliable interpretation of seismic survey data should incorporate as many seismic properties as possible.

Geodetic measurements quantifying displacement fields for the Earth’s surface illustrate a general complexity that questions the existence of a simple relationship to mantle flow and plate tectonics (e.g. Fouch & Rondenay 2006; Caporali et al. 2009; Thatcher 2009). Linking geodetically defined continental displacements to mantle flow and plate tectonics demands understanding of ductile deformation in the middle and lower continental crust, for example, the discrimination between deformation models with strongly localized ‘simple-shear’ fabrics (e.g. Burg 1999) from those involving more distributed ‘pure-shear’ crustal flow (e.g. Butler et al. 2002). Studies of the in situ seismic characteristics of the middle and lower continental crust should lead to enhanced understanding of ductile deformation in these regions. However, until recently the continental crust was considered too heterogeneous mineralogically and tectonically to reflect coherent patterns of, for example, seismic anisotropy. Today, seismic anisotropy is now not only recognized regularly in the continental crust

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Fig. 1.
but is also used increasingly to image zones of deformation (e.g. Meltzer et al. 2001; Shapiro et al. 2004; Sherrington et al. 2004; Moschetti et al. 2010). Seismic anisotropy studies (e.g. in the Himalaya and Tibet) are therefore beginning to investigate middle and lower continental crustal deformation using passive seismological experiments, such as teleseismic receiver functions (e.g. Ozacar & Zandt 2004) and records from local earthquakes (e.g. Schulte-Pelkmans et al. 2005). Such studies claim that it is possible to distinguish different types and magnitudes of deformation via seismic anisotropy. If correct, there is much to be gained from seismic (anisotropy) analysis of the (ductile) continental crust, provided the source of the anisotropy is rigorously constrained.

Although there is general agreement that measured seismic anisotropy in the middle and lower continental crust reflects bulk mineral crystallographic preferred orientation (CPO), there is a need to calibrate the seismic response to deformation structures and their kinematics (e.g. Okaya & Christensen 2002; Mahan 2006; Meissner et al. 2006). Almost all of the common rock-forming minerals in the continental crust exhibit significant seismic velocity anisotropy as single crystals (Barruol & Mainprice 1993; Ji et al. 2002). These are illustrated in Figure 1 where the individual seismic properties for each mineral have been contoured using the same scale ranges to emphasize relative values and distributions. Plotting the seismic properties in this way indicates which minerals are likely to control each seismic property (e.g. mafic minerals increase compressional wave velocity Vp while most minerals have similar seismic anisotropy AVs except for the micas, which have very high maximum anisotropy). However, for many minerals (including quartz and feldspars) crystal symmetry creates geometrically complex seismic responses that, with small degrees of misorientation within polycrystalline aggregates, interfere destructively to produce near-isotropic behaviour (Barruol & Mainprice 1993; Tatham et al. 2008; Lloyd et al. 2009). Key exceptions are monoclinic mica and amphibole minerals (e.g. biotite and hornblende) that commonly align both crystallographically and dimensionally to create a single slow direction for seismic transmission. Thus, the seismic properties measured for the (ductile) middle and lower continental crust are usually attributed to the CPO of mica (e.g. Kern & Wenk 1990; Barruol & Mainprice 1993; Nishizawa & Yoshino 2001; Shapiro et al. 2004; Mahan 2006; Meissner et al. 2006; Lloyd et al. 2009) or amphibole (e.g. Siegesmund et al. 1989; Barruol & Mainprice 1993; Rudnick & Fountain 1995; Kitamura 2006; Meissner et al. 2006; Barberini et al. 2007; Tatham et al. 2008). It should also be mentioned that other microstructural parameters (e.g. grain shape fabric and variations in spatial distribution of mineral phases, grain-boundary properties, porosity, etc.) may contribute in particular to seismic anisotropy (e.g. Wendt et al. 2003). Furthermore, in the (brittle) upper crust the effects of open fractures (e.g. Crampin 1981; Kendall et al. 2007), sedimentary layering (e.g. Vernik & Liu 1997; Valke et al. 2006; Kendall et al. 2007) and/or grain-scale effects (e.g. Hall et al. 2008) must be considered in addition to CPO.

According to recent compilations (e.g. Rudnick & Fountain 1995; Rudnick & Gao 2003), increasing average P-wave seismic velocities with depth indicates increasing proportions of mafic lithologies and increasing metamorphic grade (Fig. 2). Superposition of single-crystal Vp values for common rock-forming minerals (e.g. Fig. 1) confirms this general trend. Thus, the lower continental crust (i.e. below c. 20–25 km depth) is expected to be lithologically diverse but dominated by granulite facies mafic lithologies with an average composition approaching that of primitive basalt, although amphibolite facies may be significant where high water fluxes occur and felsic-to-intermediate lithologies can also be important locally (Rudnick & Fountain 1995). In contrast, the average middle crust (i.e. between 10–15 and 20–25 km depth), where P-wave velocities are too low to be explained by

Fig. 1. Principal seismic properties of elastically anisotropic single crystals of major rock-forming minerals relative to mineral form and crystallography (Vp: compressional wave velocities; AVs: percentage shear-wave splitting; Vs1P: polarization direction of fastest shear wave). The seismic property for each mineral has been contoured using the same scale range to emphasize relative values and distributions (i.e. Vp, minimum 5.10 km/s for plagioclase and maximum 9.77 km/s for olivine; AVs, minimum 0% and maximum 113.82% for biotite). For example, blues and reds indicate relatively high or low values respectively (NB contour lines are drawn and numbered only for the precise range of that property for that mineral). The seismic properties were derived using the Mainprice (1990) suite of programs (i.e. Pfc5, Anis and VpGC) and appropriate mineral single-crystal elastic constants: quartz (McSkimin et al. 1965), calcite (Dundekar 1968), orthoclase (Aleksandrov et al. 1974), plagioclase (Aleksandrov et al. 1974), muscovite (Vaughn & Guggenheim 1986), biotite (Aleksandrov & Ryzhova 1961), hornblende (Aleksandrov & Ryzhova 1961), augite (Aleksandrov & Ryzhova 1961), garnet (Bonczar et al. 1977) and olivine (Abramson et al. 1997).
Fig. 2. Summary of the average P-wave velocities compiled by Rudnick & Fountain (1995) for the middle (MC), lower middle (LMC), lower (LC) and lowest lower (LsC) continental crust. Also shown are the ranges (black columns) and approximate averages (white circles) of single-crystal Vp values for common rock-forming minerals (see Fig. 1). The latter can be compared to the values suggested by Rudnick & Fountain (1995) to indicate the likely minerals present and hence responsible for the seismic properties in each crustal region.

dominantly mafic lithologies, is considered to consist of a mixture of mafic, intermediate and felsic amphibolite facies gneisses (e.g. Rudnick & Fountain 1995; Rudnick & Gao 2003). Suggestions that micas control the seismic properties of the deeper continental crust (e.g. Meltzer & Christensen 2001; Meltzer et al. 2001; Takanashi et al. 2001; Chlupacova et al. 2003; Shapiro et al. 2004; Mahan 2006; Meissner et al. 2006) are difficult to reconcile with the view that there is little evidence for metapelite-dominated layers in these regions (e.g. Rudnick & Fountain 1995). Nevertheless, muscovite Vp values are clearly compatible with those expected for the lower crust rather than the middle crust (Fig. 2). In contrast, biotite values are typically too low and are more appropriate to the middle crust. It is possible that high metamorphic grade former metapelites that now comprise kyanite and/or sillimanite could also explain lower crustal Vp values; both of these minerals have high seismic velocities as well as large seismic anisotropy (e.g. Ji et al. 2002), but they probably represent <10% of the lower crust in general (Rudnick & Fountain 1995).

While single-crystal Vp characteristics of common rock-forming minerals provide initial constraints on the composition and nature of the ductile continental crust (i.e. Figs 1 & 2), actual lithologies are polygranular and usually polymineralic in reality. Thus, the Vp properties need to be derived from the whole-rock petrofabrics (i.e. the sum of the CPO for the individual constituent minerals) to provide more rigorous constraints (e.g. Barruol & Mainprice 1993). For example, combining the appropriate single-crystal Vp characteristics shown in Figure 2 indicates that granitic (i.e. quartz ± feldspars ± micas), amphibolitic (i.e. hornblende ± plagioclase ± micas) and mafic (i.e. ± amphibole ± pyroxene ± plagioclase ± garnet) compositions are responsible for the Vp properties of the middle crust, lower–middle and lower crust and lower/lowermost ductile continental crust, respectively. However, this approach omits consideration of seismic anisotropy, which typically reflects the strength of individual mineral and whole-rock CPO. In general, CPOs form in response to deformation and their detailed distributions can reflect and hence distinguish the kinematic reference frame (e.g. Schmid & Casey 1986; Pascshier & Trouw 2005). Investigation of the complete whole-rock petrofabric-derived seismic properties should therefore lead to a better understanding of ductile deformation in the middle and lower continental crust, which ultimately should help in linking geodetically defined continental displacements to mantle flow and plate tectonics. The present contribution takes up this challenge by providing constraints on the seismic properties of the ductile middle and lower continental crust via quantitative measures of CPO in appropriate natural representative samples.

Methodology

Seismic property determination

The velocity (Vp, Vs1, Vs2), anisotropy (AVp, AVs) and polarization (Vs1P) of seismic compressional (p) and shear (s) waves depend on the three-dimensional elastic ‘stiffness’ (Cij) of rocks, which varies with crystal direction in the constituent minerals (e.g. Babuska & Cara 1991). Bulk CPO and hence seismic properties are therefore determined by: individual mineral crystallography (symmetry, etc.); whole-rock mineralogy (composition, modal proportions); deformation mechanisms (e.g. crystal slip); deformation kinematics (deformation type, magnitude and rate); and geological environment (pressure, temperature, fluids, etc.). The influence of these variables is considered here via ‘end-member’ rock types that span typical middle and lower continental crustal compositions (e.g. Rudnick & Fountain 1995; Rudnick & Gao 2003), namely felsic (i.e. ± quartz ± feldspar ± mica) and mafic (i.e. ± amphibole ± pyroxene ± plagioclase ± mica). Typical samples were analysed via electron backscattered diffraction (EBSD) in the scanning electron microscope (SEM) to measure their CPOs, from which their seismic properties were derived following conventional procedures (e.g. Mainprice 1990; Mainprice & Humbert 1994; Lloyd & Kendall 2005).
**Samples**

When modelling the seismic response of the continents, we are aware that outcrop lithologies that once resided at deep crustal levels may not be representative of the lower crust in situ. Nevertheless, the samples used in this study are considered to be representative of many of the lithologies that make up the ductile middle and lower continental crust (e.g. Rudnick & Fountain 1995; Rudnick & Gao 2003). Garnet-bearing lower crustal lithologies have however been omitted from our analysis due to the isotropic seismic properties and relatively high density of garnet which predictably act to dilute seismic anisotropy and increase seismic (P-wave) velocity (e.g. Figs 1 & 2), respectively, with increasing garnet content (e.g. Brown et al. 2009) even if the garnet exhibits (rare) CPO. In addition, we consider orthopyroxene (specifically hypersthene) to be representative of pyroxenes generally due to the similarity in crystal structure and hence seismic properties of orthopyroxenes and clinopyroxenes (see Barruol & Mainprice 1993 or Ji et al. 2002 for specific examples). The four samples used in this study are described as follows.

1. **Felsic orthogneiss** (Nanga Parbat, west Himalaya; Butler et al. 2002). This rock comprises quartz–orthoclase–plagioclase–biotite–muscovite. Such orthogneisses are derived largely from a granodioritic protolith composed of feldspar, quartz and biotite, with subordinate muscovite. Overall, this composition is considered to represent a good analogue for much of the Earth’s ductile hydrous middle continental crust. Furthermore, mica-bearing tectonites frequently exhibit S–C fabrics, which allow the impact of different textural development on seismic properties to be investigated (Lloyd et al. 2009).

2. **‘Banded’ amphibolite** (south Harris, northwest Scotland; Lapworth et al. 2002). This rock comprises hornblende–plagioclase–quartz. The compositions of different ‘bands’ (e.g. quartz–plagioclase, quartz–plagioclase–hornblende, plagioclase–quartz–hornblende, hornblende–plagioclase–quartz, hornblende–plagioclase and hornblende only) are considered to be representative of a range of hydrous ductile middle-to-lower continental crustal lithologies.

3. **Sheared mafic dyke** (Badcall, northwest Scotland; Tatham & Casey 2007; Tatham et al. 2008). This rock comprises hornblende–plagioclase–quartz and is therefore apparently compositionally similar to sample 2. However, it represents a suite of specimens (1–9; note specimen 1 contains also appreciable clinopyroxene that presumably reflects the original igneous composition) exhibiting progressively increasing deformation. It is therefore used to study the impact of deformation on seismic properties. It is considered to be representative of the hydrous ductile upper–mid lower continental crust.

4. **Pyroxene granulite** (Kerala, south India; Prasannakumar & Lloyd 2007, 2010). This rock comprises hypersthene–plagioclase–quartz–(biotite). It is considered to be representative of the anhydrous (hydrous where micaceous) ductile lower continental crust.

**Results**

**Composition and texture**

The effective database of whole-rock CPO and hence seismic properties can be expanded by a modelling approach that utilizes ‘rock recipes’ based on the mineral modal proportions determined via SEM-EBSD analysis (e.g. Tatham 2008; Tatham et al. 2008; Lloyd et al. 2009). In this approach, the modal content of one mineral is varied progressively from 0 to 100% while the other phases are varied according to their original modal proportions. The seismic properties are then calculated per ‘recipe’. The recipes considered here are based on nine specimens comprising hornblende, plagioclase and quartz collected from sample 3 above, the sheared mafic dyke rock (Tatham & Casey 2007; Tatham 2008). The CPO (not shown here – see Tatham et al. 2008) of the individual minerals in these specimens was determined via SEM-EBSD, from which the whole-rock seismic properties per specimen were determined in the conventional manner (see above). In general, the specimens exhibit a trend in seismic properties from an almost isotropic aggregate (specimen 1) to a strong and ordered pattern of orthorhombic symmetry (specimens 2–9) with increasing strain that accords with the finite strain axes and indicates the dominant role of hornblende in controlling these properties (e.g. Tatham et al. 2008). However, the roles played by all three constituent minerals can be investigated, both within and across the range of specimens from sample 3, via a rock-recipe modelling approach as follows.

**Rock-recipe modelling.** As the specimens of sheared mafic dyke rock typically comprise only three mineral phases (i.e. hornblende, plagioclase and quartz), modelled variations in their compositions can be represented by simple ternary plots (see Fig. 3). Each plot is based on the interpolation of monomineralic aggregate elastic properties for the specimen over all permutations of modal fractions,
including monomineralic, in each mineral phase. However, the elastic properties of each mineral phase are representative of their deformation behaviour in a polyphase aggregate with the specific relative modal volume fractions of the original specimen. In practice, both the strain distribution

Fig. 3. Ternary rock-recipe plots for mafic dyke samples 1–9 showing the sensitivity of various seismic properties to variations in modal composition for different shear strains ($\gamma$) and ellipticity ($R$) of the finite strain ellipse in a three-phase aggregate system comprising hornblende, plagioclase and quartz. The shaded areas of the legend ternary plots indicate the regions of confident extrapolation of data due to potential differences in the behaviour of polyminalric and monomineralic rocks (see text for discussion). Black dots indicate the actual modal composition of each sample. (a) Maximum in $V_p$; (b) $AV_p$; (c) $AV_s$. 
in the original specimen and its partitioning into specific mineral phases are likely to be such that the microstructure, petrofabric and hence elastic properties of the constituent mineral phase fractions are not representative of the behaviour of each phase for a monomineralic rock of that phase at the strain observed in the bulk specimen. For example, deformation of an aggregate comprising 60% hornblende, 30% plagioclase and 10% quartz (similar to that of specimens 19; see Fig. 3) seems to preferentially partition strain into the hornblende phase as the plagioclase and quartz phases exhibit poorly developed CPO (see Tatham 2008; Tatham et al. 2008). Deformation of approximately monomineralic aggregates of either quartz or plagioclase to the same bulk strain would almost certainly involve the development of strong CPO (e.g. Marshall & McLaren 1977a, b; Lister & Dornsiepen 1982; Olsen & Kohlstedt 1984, 1985; Mainprice et al. 1986; Kruhl 1987).

The range of relative modal fractions (i.e. rock recipes) for which the ternary plots (Fig. 3) can be applied is therefore likely limited. From results of low-law calculations in a selection of two-phase aggregates, Handy (1994) postulated that the presence of >10% of a weak phase is necessary for that phase to govern the bulk strength of the aggregate. In detail, this prediction depends on a number of factors including temperature, strain rate and the strength contrast between adjacent phases. It is therefore suggested that the rock-recipe modelling results are accurate only between 10 and 90% in each phase for each possible two-phase system of the three-phase aggregate (i.e. the shaded areas indicated in the legend ternary plots in Fig. 3).

The ternary rock-recipe plots reveal the sensitivity of various seismic properties to variations in modal composition for different deformation states (e.g. shear strain and ellipticity of the finite strain ellipse). It is clear that the maxima in Vp, AVp and AVs are most strongly dependent upon hornblende modal fraction. For example, there are increases of up to 1 km/s in Vp (Fig. 3a), 5% in AVp (Fig. 3b) and 8% in AVs between end-member plagioclase and hornblende compositions.

Figure 3a, b also indicates that both AVp and AVs tend to increase with increasing strain, but only up to a shear strain of c. 10. Beyond this value there tends to be little increase in either anisotropy. This behaviour suggests that seismic anisotropy cannot increase indefinitely with deformation, but saturates at a certain value. In general, Vp values show little variation with increasing strain (Fig. 3a).

In contrast, the impact of changing quartz modal fraction on these seismic properties is minor. For example, from a starting aggregate of 50% hornblende and 50% plagioclase, progressively increasing the quartz fraction up to 100% yields only a 2% increase overall in AVp (Fig. 3b) and a 2% increase in AVs at 50% quartz, returning to no increase at 100% quartz (Fig. 3c). The change in the maximum in Vp is also minimal (Fig. 3a). Previous investigations into the relative effects of component phases on seismic properties have also highlighted the dominant role of mafic components (e.g. hornblende) compared to felsic components (plagioclase and quartz), with the latter often acting as ‘dilutants’ (e.g. Christensen & Fountain 1975; Fountain & Christensen 1989; Tatham et al. 2008; Lloyd et al. 2009).

Rock-recipe modelling approaches indicate that the seismic properties of (hydrous) mafic rocks are most likely to be controlled by amphibole (e.g. Tatham et al. 2008). In contrast, for felsic rocks, micas (in particular biotite) are the controlling mineral phase (e.g. Lloyd et al. 2009, 2011). Other minerals in both lithologies, such as plagioclase and quartz but also pyroxene (see below), act as dilutants and tend to reduce seismic properties (particularly anisotropy) although some (e.g. plagioclase and pyroxene) may increase velocities (see below).

**Fabric-recipe modelling.** Many rocks may comprise different deformation fabrics (e.g. S–C foliations). Use of fabric recipes based on subsets of individual rock fabric CPOs therefore allows the impact of different fabrics on seismic properties to be investigated. In this recipe modelling approach, CPOs are measured (e.g. via SEM-EBSD) for each fabric element and also for the whole rock, and are then varied in a similar manner to rock recipes. The elastic properties of each fabric recipe are then used to calculate the impact of different proportions of each fabric on the whole-rock seismic properties. For example, Lloyd et al. (2009, 2011) have shown that the typical transverse isotropy characteristics associated with individual mica fabric elements can disappear in whole rocks comprising S–C type foliations.

**Foliation and azimuthal effects**

**Seismic modelling.** Rock and fabric-recipe modelling suggest that foliation, and in particular its orientation, exerts a significant impact on seismic properties (see also Lloyd et al. 2011). To investigate this impact, a seismic model was constructed representing a 10 km slice of deformed lower continental crust (Fig. 4). This thickness of crust was chosen to provide practical values of shear-wave splitting (dVs). The model was populated with the elastic stiffness properties of the nine specimens of mafic dyke rock using a common rock-recipe composition of 60% hornblende, 30% plagioclase and 10% quartz, which represents the average composition of these specimens.
As discussed previously, the elastic properties of rock sample 3 vary due to the increasing strain exhibited by specimens 1–9 (e.g. Fig. 3). One axis of the model can therefore be scaled according to increasing strain, represented as either shear strain (γ) or the length of the major axis of the strain ellipse (S1, where S1 = 1 defines an undeformed unit circle). Representing the variation in seismic properties with respect to either γ or S1 means that the plots can be used to consider either simple or pure-shear-dominated deformations, respectively. The other axis of the model is scaled according to the orientation of sample foliation relative to propagating seismic waves. For the purposes of this model it is assumed that the waves propagate vertically through the 10 km of crust and can effectively be considered as teleseismic waves (Fig. 4). Sample foliation is rotated from horizontal (0°) to vertical (90°) in both clockwise and anticlockwise directions about either the X or Y tectonic axes. In the former configuration, the X or lineation axis remains unchanged and horizontal while the foliation rotates from horizontal to vertical. In the latter configuration, both the lineation and foliation rotate between horizontal and vertical.

The variation in seismic properties with strain and foliation orientation in the model is determined in three stages (e.g. Fig. 4). Firstly, the bulk elastic stiffness matrices (Cij) for each specimen of deformed mafic dyke rock are interpolated between their pre-determined finite shear strains (γ) or the associated strain ellipse long axes (S1) to describe the variation of elastic stiffness with strain. The interpolated grid is discrete but of high resolution, with interpolations at increments of 0.1 for both γ and S1. Secondly, the interpolated strain scale of Cij is incrementally rotated from 0° to 90° either clockwise or anticlockwise with respect to either the X or Y tectonic axes. Again, the interpolated scale of petrofabric rotation is discrete but of high resolution, with increments of ±5°. Thirdly, the values of Vp and dVs are calculated for each node of the interpolated grids, from which contoured plots are constructed (e.g. Fig. 4). Note that the calculated P-wave velocities refer specifically to vertically propagating waves and hence are not necessarily the maximum in P-wave velocities. In addition, the fast shear-wave polarization orientation (Vs1P) is also determined, but for a more sparsely populated grid necessary for display purposes.

**Foliation orientation.** Results of seismic modelling of the impact of foliation orientation on seismic properties (Vp and dVs) for different strains (i.e. 'simple' and 'pure' shears) are shown in Figure 5. In general, all relationships indicate a crude bilateral symmetry about the line of zero rotation (horizontal foliation). Deviations from perfect bilateral symmetry are due to a combination of the slightly non-orthorhombic nature of the aggregate Cij, which probably reflects complex interactions between constituent phases with different seismic properties and symmetries and other natural variations (e.g. microstructure, CPO, etc.). Apparently anomalous steps or jumps in the distribution of seismic properties are an amplification effect of specimen variations. Discontinuities in the smoothly varying distributions mark points of specimen control, while smooth variations denote regions of interpolation of physical properties between specimens. Similarly, complex patterns of 'peaks' and 'cusps', particularly within central bands adjacent to the symmetry axis, are due to local effects around specimen control points. The peaks and cusps are of comparatively low relief and are considered to be insignificant with respect to the overall trends indicated. The impact of each of these irregularities would be reduced by employing a greater specimen density. If they are overlooked, a number of
Fig. 5. SEISMIC PROPERTIES OF CONTINENTAL CRUST
significant trends in the seismic properties can be recognized as follows (see Fig. 5).

(1) The bilateral symmetries recognized in all plots suggest that the direction of fabric rotation (i.e. clockwise or anticlockwise) about the kinematic X or Y axes does not affect the pattern or magnitude of seismic velocity or anisotropy to any significant degree. Furthermore, there are notable similarities between the velocity and anisotropy distributions irrespective of whether the foliation is rotated about either the X or Y axes.

(2) There is a general decrease in the magnitude of seismic velocity and anisotropy with increasing strain for subhorizontal foliation orientations. This contrasts with the tendency for velocity and anisotropy values to increase with strain for steep to vertical foliations orientations. The greatest rate of change occurs for values $0 \leq \gamma \leq 10$ or $1 \leq S1 \leq 3$, beyond which increasing strain results in negligible changes in either velocity or anisotropy. This observation supports the suggestion made earlier that both petrofabric and hence petrophysical properties become saturated by $\gamma$ c. 10 (i.e. $S1 \approx 3$).

(3) Somewhat steeper gradients in the change in Vp and dVs with strain are observed for values $0 \leq \gamma \leq 0.4$ or $1 \leq S1 \leq 1.2$. These behaviours suggest that small initial strains imposed upon initially isotropic protoliths can have dramatic effects upon the seismic properties.

(4) The change from dominantly decreasing to increasing trends of Vp and dVs values with strain occurs for foliation rotations about X of 20–40°. Similar behaviour is shown by Vp for rotations about Y. For dVs the change occurs closer to 60° due to details in the AVs distribution, whereby low values of anisotropy occupy a greater proportion of the XZ plane compared to the YZ plane; this leads to a comparatively wider band of low dVs values about subhorizontal foliations. It therefore follows that, for a given strain, a move from subhorizontal to subvertical foliations is associated with an overall increase in Vp and dVs values.

Based on these seismic modelling results, interpolation of the petrophysical properties of a discrete strain-calibrated microstructurally characterized and compositionally normalized suite of specimens allows the evaluation of seismic properties against finite strains (both simple and pure shears) and foliation orientation in that material, across a continuum. A similar conclusion, again based on petrofabric-derived seismic modelling, is reported elsewhere in this volume for mica-dominated felsic rocks (Lloyd et al. 2011). It therefore appears that CPO observations and Vp and dVs (sic AVs) distributions are potentially useful proxies for each other in regional-scale crustal geodynamic investigations and models.

**Azimuthal considerations.** In the previous section it was shown that accurate interpretation of seismic wave propagation through foliated rocks depends on knowledge of the source and propagation direction of the seismic waves relative to the foliation orientation. The propagation direction was always vertical in the seismic model described above, implying either teleseismic waves or possibly local seismic events. In nature, source locations are likely to be variable and hence propagation directions also vary in their orientations (i.e. azimuths and plunges). For example, assuming a constant steeply dipping foliation, waves from a teleseismic source would propagate (sub-) parallel to foliation while waves from a remote (i.e. ‘wide-angle’) source would propagate (sub-) normal to foliation. The same seismic array would therefore detect very different seismic properties. This simple example emphasizes the need to also consider CPO-derived polarization/birefringence (i.e. Vs1P) effects in the seismic models.

Analysis of Vs1P behaviour for the seismic model (Fig. 4) reveals distributions similar to those of Vp and dVs (Fig. 6). The vertical expression of shear-wave polarization becomes more apparent with increasing strain and as the foliation rotates towards the vertical. Furthermore, as indicated in the previous section, Vs1P is also associated with an increasing component of the total AVs as the foliation rotates towards parallelism with the vertical wave propagation direction. However, the direction of rotation does produce some differences. For rotations about X, the direction of polarization is ‘parallel’ to the strain axis of the plots which effectively defines the orientation of X (Fig. 6a). In contrast, for rotations about Y, the direction of polarization is ‘normal’ to the strain axis of the plots which effectively defines the orientation of Y (Fig. 6b). These results are perhaps intuitive and reflect the development of an increasingly well-defined foliation with strain, together with the increasing parallelism of that foliation with the seismic ray-path. The Vs1P polarization plane is consistently parallel to the plane of petrofabric foliation (Fig. 6 inserts), which in turn is parallel to the girdle of greatest shear-wave anisotropy.

The seismic modelling described here illustrates the significance of azimuth in the interpretation of seismic properties. A similar conclusion, again based on petrofabric-derived seismic modelling, is reported elsewhere in this volume for
mica-dominated felsic rocks (Lloyd et al. 2011). However, in that contribution, it is shown that rocks comprising multiple (mica-defined) foliations exert complicated responses on Vs1P orientations and magnitudes, varying with the relative proportions of the different foliations (see also Lloyd et al. 2009). In particular, the VS1P orientation does not necessarily reflect variations in kinematics indicated by changing foliation proportions. It therefore appears that CPO observations and seismic property distributions are potentially useful proxies for each other, but only in regional-scale crustal geodynamic investigations and models involving a single and/or dominant foliation. In regions comprising multiple foliations, which are likely to generate variations in orientation and magnitude of both AVs and VS1P, ‘maps’ of variations in these properties with depth need careful (geological) consideration and interpretation.

**CPO and deformation**

CPO develops during ductile deformation via dislocation creep on crystal slip systems that are mainly temperature dependent, but are also sensitive to deformation type (e.g. Nicolas & Poirier 1976; Passchier & Trouw 2005). Complex natural deformations are usually simplified (e.g. plane strain, pure and simple shear, flattening, constriction, etc.) and represented on diagrams such as Flinn plots (e.g. Flinn 1956; see below and Figs 7 & 8). However, these deformations may not always be distinguished via the seismic properties of the dominant minerals, as the following examples indicate.

Figure 7a is a Flinn diagram illustrating the variation in quartz c- and a-axes CPO with deformation type and magnitude (Lister & Hobbs 1980). Note the tendency for dispersion rather than concentration.
into unique directions of the crystal axes. These
dispersions are responsible for the ‘diluting’ effect
of quartz on whole-rock CPO. Simply stated, the
elastic anisotropy due to minerals such as quartz
(which do not form ‘quasi-single-crystal’ CPO) is
distributed rather than concentrated such that both
the whole-rock velocity and anisotropy of seismic
waves are reduced. This effect is indicated clearly
in Figure 7b, which is a Flinn plot representation
of the Vp and AVs seismic properties for different
quartz CPOs due to different deformations.

The approach illustrated in Figure 7 for quartz
can be extrapolated to the seismically important
mica and amphibole minerals as follows. In
general, natural CPO data for either mica or amphi-
boles are lacking when compared to that
available for quartz. However, it is possible to
model the CPO expected for different deformations
due to the simple relationship between mica/amphi-
boles and the crystal axes. In effect, the
shape of the mineral grains accurately reflects the
direction of the crystal axes. Both mineral groups
therefore tend to form quasi-single-crystal CPO
during deformation (e.g. Tatham et al. 2008; Lloyd
et al. 2009), involving the operation of relatively
few and simple crystal slip systems. These systems
are (001) <110> and/or (001)[100] for micas and
(100)[001], (010)[001] or (hk0)[001] for amphi-
boles (e.g. Nicolas & Poirier 1976). Furthermore,
due to the simple relationship between mineral
grain shape and crystal axes orientations, both
mineral groups may also develop similar CPO via
rigid-body rotation rather than crystal slip (e.g.
Meissner et al. 2006; Díaz-Azpíroz et al. 2007;
Tatham et al. 2008).

For flattening type deformations (i.e. where the
Flinn K parameter approaches zero such that the
tectonic axes have the relationship
X ≈ Y ≫ Z,
leading to S-type tectonites), both micas and amphi-
boles are expected to form strongly foliated rock
fabrics. Consequently, their CPOs are characterized
by uniform distributions of a (001)/b (010) and
b (010)/c (001), respectively, with the mica c (001)
axis and the amphibole a (100) axis defining the foli-
ation normal (Fig. 8). These CPOs lead to so-called
vertical transverse isotropy or VTI seismic distri-
butions for Vp and AVs, with maximum values in
both symmetrically distributed parallel to foliation.
The minimum in Vp is normal to foliation in both
mineral groups. However, the minimum in AVs is

Fig. 7. Left: idealized Flinn plot indicating the expected variation in quartz c- and a-axes CPO with different types
and magnitude of deformation (Lister & Dornsiepen 1982). Note the tendency for dispersion rather than concentration
of crystal axes. Right: Flinn plot representation of examples of natural quartz c- and a-axes CPO and the resulting
Vp and AVs seismic properties (data from G. E. Lloyd archive).

Fig. 8. Idealized ‘Flinn-type’ plots of (a) biotite and (b) hornblende CPO and their derived seismic properties for
‘flattening’, ‘simple-shear’ and ‘constriction’ deformations. Note: 1. biotite-controlled Vp and AVs are sensitive only to
foliation due to mica VTI symmetry and therefore can distinguish only constriction deformation; 2. hornblende-
controlled Vp and AVs are sensitive to foliation and lineation due to ‘orthorhombic’ symmetry and can therefore
distinguish different deformations.
Constriction \( K = \frac{c}{a} \)

Flattening \( K = 0 \)

Plane strain \( K = 1 \)

(a) 

- Prolate ellipsoid
  - \( X >> Y = Z \)
  - Constriction
  - L-tectonite

(b) 

- Oblate ellipsoid
  - \( X = Y >> Z \)
  - Flattening
  - L-tectonite

Fig. 8.
normal to foliation only for amphiboles; for micas, it defines a small circle inclined to the foliation normal. For both minerals, the orientation of Vs1P is radial for waves propagating subvertical to foliation but becomes circumferential for waves propagating subparallel to foliation.

For plane strain deformations (i.e. \( K \sim 1 \) and \( X > Y > Z \), leading to LS-type tectonites) micas and amphiboles are expected to form both foliated and lineated rock fabrics. Consequently, their CPOs are characterized by quasi-single-crystal distributions in which (100) and [001] are parallel to lineation and foliation normal for micas, respectively, but this relationship is reversed for amphiboles (Fig. 8). In both mineral groups, (010) also lies within the foliation. Thus, as both (100) and (010) lie within the foliation and due to the VTI characteristics of the single crystal (Fig. 1), the seismic properties for micas exhibit exactly the same distributions as for the previous case (Fig. 8). It is therefore not possible to distinguish between deformations defined by \( 0 < K \sim 1 \) on the basis of mica seismic properties. However, amphibole single crystal do not exhibit VTI (Fig. 1); the CPO-based seismic properties are therefore different from the previous case and can distinguish both foliation (with the foliation normal defined by the minimum in both Vp and AVs) and lineation (defined by the albeit slight maximum in both Vp and AVs). The orientations of Vs1P for amphiboles are parallel to the YZ plane for waves propagating subvertical to foliation and circumferential for waves propagating subparallel to foliation (i.e. there is no indication of lineation).

For constrictional deformations (i.e. \( K \rightarrow \infty \) and \( X \gg Y \sim Z \), leading to L-type tectonites) micas and amphiboles are expected to form strongly lineated rock fabrics. Consequently, their CPOs are characterized by strong concentrations of the principal crystal slip directions (i.e. (100) in micas and [001] in amphiboles) parallel to the tectonic extension (X) direction (Fig. 8). However, due to the fact that foliation development is impeded, neither [001] of micas nor (100) of amphiboles form orientation clusters but tend to form, with (010) in both minerals, great circle CPO distributions normal to X. The resulting CPO-based seismic property distributions are therefore different to previous cases for both mineral groups (Fig. 8). They both show maximum in Vp parallel to X and a very diffuse spread of low Vp velocities parallel-to-oblique to the foliation. In contrast, it is the minimum in AVs that aligns parallel with X for both mineral groups, while the foliation plane is defined by a narrow great circle of intermediate values for micas and a more diffuse great circle of alternating low-to-intermediate values for amphiboles. The orientation of Vs1P for micas is consistently parallel to XY for all propagation directions subparallel to this plane; for all other propagation directions it is typically circumferential. For amphiboles, the orientation of Vs1P is parallel to either XZ or YZ for all propagation directions within these planes, leading to a complex interference pattern for vertically propagating (i.e. teleseismic) waves. For all other propagation directions, Vs1P is oriented circumferentially.

Figure 8 illustrates that it may be difficult (if not impossible) to distinguish seismically between plane strain and flattening type deformations in micaceous (i.e. felsic) rocks due to the similarity of their CPO-based seismic property distributions, which results from the VTI characteristics of mica single crystals. However, constrictional type deformations, which are likely to be rarer in nature, can be easily recognized via their distinctive CPO-based seismic property distributions. In contrast, there is a difference between CPO-based seismic property distributions for plane strain and flattening deformations in amphibolitic (i.e. mafic) rocks, although this may often be subtle, while constrictional deformations yield very different distributions. These observations suggest that seismic property distributions can be used as proxies for deformation types and hence are potentially able to distinguish geodynamic behaviour in mafic lithologies dominated by amphibole. Figure 8 also emphasizes the significant impact foliation development has on influencing the (observed) seismic properties, supporting observations presented above (e.g. Figs 5 & 6). Indeed, it is the absence of foliation that results in the distinctive seismic responses of amphiboles and particularly micas for constrictional deformations.

**Modelling seismic properties of ductile continental crust**

This section considers the implications of the results presented above for the explanation and interpretation of the seismic properties of the ductile continental crust using the CPO-derived seismic properties (specifically Vp, AVp and AVs) of the four rock samples described previously. It is emphasized that the controlling variables constraining the seismic properties appear to be: (1) the single-crystal elastic constants of the individual rock-forming minerals as reflected in the modal composition; (2) CPO; (3) foliation development and orientation; and (4) deformation type.

**Compressional wave velocities**

Rudnick & Fountain (1995) suggested the following Vp ‘stratigraphy’ for the ductile continental crust...
Fig. 9. Constraints on the seismic properties of the middle and lower ductile continental crust based on CPO and rock-recipe modelling of: (a) felsic orthogneiss (biotite variable modal content); (b) biotite-bearing pyroxene granulite (biotite variable modal content); (c) mafic dyke (hornblende variable modal content); and (d) pyroxene granulite (hypersthene biotite variable modal content). All samples are deformed. Also shown are the typical Vp ranges (broken lines) for different parts of the middle-to-lower crust as suggested by Rudnick & Fountain (1999). See text for discussion.

It appears that neither mica content nor deformation can account for the Vp values observed in the middle and lower continental crust, which therefore must be due to other minerals. From Figure 1, the most likely candidates are quartz and particularly feldspars, unless the rocks also consist of a mafic mineral. However, increasing the whole-rock Vp is not simply a matter of adding common rock-forming minerals that possess relatively high Vp as a rock-recipe model for the pyroxene granulite sample indicates (Fig. 9b). Although this rock...
comprises only minor biotite, its V_p values only satisfy those expected for the middle crust for the actual rock composition. Increasing the biotite content gradually decreases the maximum in V_p but significantly decreases the minimum in V_p, such that most values of V_p fall below those expected for the middle crust.

Amphibole is clearly capable of explaining V_p values throughout the whole ductile continental crust (Fig. 9c). Indeed, it does not matter whether layering (i.e. foliation) is flat lying or steep, V_p values are still well within limits. Rocks with very high amphibole contents could account for the V_p values observed in the deepest regions of the continental crust (i.e. in excess of 7 km/s). If this interpretation is correct, it implies that these regions are also hydrous. However, mafic anhydrous minerals (and in particular pyroxene) can contribute even more strongly to V_p values due to their single-crystal characteristics (Fig. 1) and are capable of achieving velocities up to 8 km/s in overtly pyroxene-dominated lithologies (Fig. 9d). It is therefore not possible to reconcile between amphibole and pyroxene as the specific cause of V_p values observed in the ductile continental crust, except where velocities exceed perhaps 7.5 km/s. Such high velocities might also be explained by increasing garnet content, although with concomitant decrease in anisotropy (e.g. Brown et al. 2009).

P- and S-waves anisotropy

Unlike velocity, seismic anisotropy (both AV_p and AV_s) is not dependent directly upon depth as it tends to reflect CPO development and hence magnitude of deformation rather than mineralogy per se. Nevertheless, it is clear that micas are the most seismically anisotropic of the common rock-forming minerals, with maximum AV_p and AV_s values (for biotite) of up to 64 and 114% respectively (see Fig. 1). This suggests that felsic rocks with well-aligned micas should be the most anisotropic. The sample of felsic orthogneiss (Fig. 9a) supports this suggestion, showing rapid increase in AV_p and particularly AV_s with increasing biotite modal content. Similar behaviour is also shown by progressively increasing the initial minor biotite content in the pyroxene granulate sample (Fig. 9b). Indeed, although mica (specifically biotite) contents in excess of c. 30% are unusual (except perhaps in slates), even normal modal contents of say 10–25% are more than capable of contributing significant anisotropy.

In contrast, amphibole modal contents of 10–25% appear to be capable of contributing only relatively low values of AV_p and AV_s (Fig. 9c). However, for modal amphibole contents above c. 35%, both AV_p and AV_s increase rapidly and approach similar values to those due to mica (biotite) for >60% amphibole. As amphibole modal contents of c. 60% may not be unusual naturally, amphibole can therefore be regarded as a potential source of AV_p and AV_s in the ductile continental crust.

The contribution of pyroxenes to anisotropy, as indicated by the pyroxene granulate sample, appears to be opposite to both micas and amphiboles. For this particular sample, AV_p remains approximately constant with increasing pyroxene content but AV_s decreases progressively and eventually converges on the AV_p value (Fig. 9d). As this sample is deformed and the pyroxene exhibits a relatively strong CPO, it therefore seems that pyroxene content may have little or no impact on AV_p and a negative impact on AV_s. This behaviour is perhaps explained by recalling that pyroxene exhibits significantly less single-crystal anisotropy, particularly in AV_s, compared to other common rock-forming minerals (e.g. Fig. 1). For example, for augite AV_p = 24.3% and AV_s = 18.0% but for hornblende AV_p = 27.1% and AV_s = 30.7%. This suggests that pyroxene-dominated lithologies are not as anisotropic as their amphibolitic counterparts, which is likely to have significant implications for the seismic anisotropy of the lower continental crust.

Finally in this section, it should be recognized that AV_s is critically azimuthally dependent, whereas AV_p has no azimuthal dependence and merely represents the absolute difference between the maximum and minimum in V_p. For example, shear waves propagating normal to foliation exhibit significantly lower AV_s than the maximum possible (e.g. Fig. 5), which argues that crustal regions dominated by (sub-) horizontal layering (i.e. much of the lower continental crust according to Rudnick & Fountain 1995) should exhibit relatively low AV_s values irrespective of mineralogy (e.g. Tatham 2008; Lloyd et al. 2011; Diaz-Azpiroz et al. 2011). It is therefore important to incorporate also propagation direction (i.e. AV_s combined with V_s1P) when considering and/or interpreting AV_s from continental regions. The samples described in this section were considered simply in terms of their bulk AV_p and AV_s characteristics as functions of composition alone (e.g. Fig. 9). In the next section, two of these samples – the ‘banded’ amphibolite and the pyroxene granulate – are considered as microcosms of layered continental crustal sections, so-called ‘seismic stratigraphy modelling’ in which case the azimuthal dependence of AV_s can be incorporated.

Seismic stratigraphy modelling

The sample of ‘banded’ amphibolite used to construct Figure 9c comprises hornblende, plagioclase
and quartz. However, these minerals have combined together in different proportions to form alternating bands of different compositions. In effect, this layered structure mimics the compositional changes from felsic to mafic lithologies expected with increasing depth through the ductile continental crust (e.g. Rudnick & Fountain 1999), although admittedly not in actual sequence in the sample. By defining and analysing separately individual layers/lithologies, their CPOs can be used to derive their particular seismic properties from which a ‘seismic stratigraphy’ for Vp, AVp and AVs can be constructed and used to model the seismic response of the middle and lower continental crust (Fig. 10).

Although not layered, a similar modelling approach to that used for the banded amphibolite can be applied to the pyroxene granulite based on rock-recipe variations in modal pyroxene, plagioclase and biotite compositions. The seismic stratigraphy that can be constructed from this sample can be used to model (Fig. 11) the seismic response of not only mafic and felsic lower continental crust but also potential anhydrous and hydrous variants (i.e. pyroxene granulite or pyroxenite, as opposed to biotitic anorthosite granulite or biotitic pyroxene granulite).

**Middle-to-lower crust (‘banded’ amphibolite).** Figure 10 is a potential CPO-derived Vp, AVp and AVs seismic stratigraphy for a middle-to-lower continental crustal section. In terms of Vp (Fig. 10a), values increase progressively as composition changes from felsic (i.e. plagioclase–quartz dominated) to mafic (i.e. hornblende–plagioclase dominated) and eventually to ultramafic (i.e. hornblende dominated). These values encompass the range of velocities suggested as being typical of the middle and lower crust (e.g. Rudnick & Fountain 1999) and are also in close agreement with the results obtained from rock-recipe modelling of the sheared mafic dyke sample (Fig. 9c).

In terms of anisotropy (Fig. 10b), both AVp and AVs values are relatively low for felsic (i.e. plagioclase–quartz dominated) compositions, with AVp noticeably smaller than AVs. With an increasing mafic (i.e. hornblende) component, AVp increases initially only slowly while AVs decreases slightly.

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**Fig. 10.** Constraints on the seismic properties of the middle and lower ductile continental crust based on CPO and rock-recipe modelling of individual compositional bands in a deformed ‘banded’ amphibolite, taken to simulate a middle to lower continental crust compositional profile (i.e. felsic to mafic compositions). Also shown (grey) are the results from Figure 9c of ‘rock-recipe’ modelling for amphibole (hornblende) content in the mafic dyke sample and typical Vp ranges for different parts of the middle-lower crust as suggested by Rudnick & Fountain (1999). See text for discussion. (a) P-wave velocity; (b) P- and S-waves anisotropy.
and becomes less than AVp for intermediate compositions (i.e. \( c \cdot 1/3 \) mafic content). At \( c \cdot 0.5\% \) mafic content, AVs exceeds AVp and increases more rapidly towards ultramafic (i.e. so-called ‘hornblende’) compositions. These results are in broad agreement with the behaviour exhibited by the mafic dyke, including the tendency for AVs < AVp for felsic compositions (Fig. 9c).

Due to the azimuthal dependence of AVs, simply plotting maximum values of shear-wave splitting can be misleading (e.g. Fig. 6). This situation is exacerbated by the impact of foliation and/or compositional layering orientation (e.g. Figs 5 & 8). To emphasize this effect, the layering in the banded amphibolite sample has been considered to be oriented horizontally in a geographical sense. For a vertically propagating (i.e. teleseismic) shear wave, the value of AVs for each composition is significantly smaller (i.e. from 2% to 3%) than the maximum recorded (Fig. 10b). Indeed, for most compositions it is smaller than the azimuthally independent absolute P-wave anisotropy. Furthermore, the polarization direction of the fast (teleseismic) shear wave (i.e. Vs1P) is not constant and changes through 90° as the composition changes from felsic to intermediate, beyond which it remains constant. This behaviour of Vs1P clearly reflects the increasing influence of the amphibole (hornblende). From Figure 8b, this would indicate not only a horizontal foliation/Layering (as initially defined) but also an ‘east–west’ (in the arbitrary coordinate system assumed) tectonic Y-direction and hence a ‘north–south’ oriented lineation. Thus, this banded amphibolite sample can be interpreted from the CPO-derived seismic characteristics as being an LS tectonite that developed under conditions close to plane strain (i.e. \( K \sim 1 \)).

Lower crust (pyroxene granulite). Figure 11 is a potential CPO-derived Vp, AVp and AVs seismic stratigraphy for a lower continental crustal section. In terms of Vp (Fig. 11a), values increase progressively as composition changes from felsic (i.e. biotite–plagioclase dominated) to mafic (i.e. pyroxene dominated) and eventually to ultramafic (i.e. so-called ‘pyroxenites’). However, the most felsic compositions (e.g. biotitic anorthosite granulite) exhibit Vp values less than those expected for even the middle crust, while compositions between

![Fig. 11. Constraints on the seismic properties of the middle and lower ductile continental crust based on CPO and rock-recipe modelling of individual compositional bands in a deformed pyroxene granulite, taken to simulate in particular a lowermost middle to lowest continental crust compositional profile. The presence of biotite in some ‘bands’ permits not only felsic to mafic compositions but also hydrous to anhydrous conditions to be considered. Also shown (grey) are the results from Figure 9d of ‘rock-recipe’ modelling for pyroxene (hypersthene) content in this rock and typical Vp ranges for different parts of the middle-lower crust as suggested by Rudnick & Fountain (1999). See text for discussion. (a) P-wave velocity; (b) P- and S-waves anisotropy.](image-url)
bipartite anorthosite granulite and bipartite pyroxene granulite yield Vp values typical of the middle crust (e.g. Rudnick & Fountain 1999). In general, essentially mafic compositions (i.e. bipartite pyroxene and pyroxene granulites) are required to produce typical lower crustal Vp values. Ultramafic compositions exhibit Vp values in excess of those expected in typical lower crust.

In terms of anisotropy, AVp is relatively small for felsic (i.e. biotite–plagioclase dominated) compositions but AVs is much larger (Fig. 11b). As the mafic component steadily increases towards pyroxene-dominated compositions, AVp remains essentially constant but AVs reduces significantly and therefore trends towards AVp. These results are obviously in broad agreement with those shown in Figure 9c due to the fact that the same sample is involved in both. However, there are some differences because the seismic-stratigraphy compositions have been defined via rock recipes.

To investigate the impact of azimuthal dependence on AVs, the sample of pyroxene granulite (which is an XZ tectonic section) is considered to have been oriented with X horizontal and Z vertical geographically (i.e. horizontal foliation and/or layering). For a vertically propagating (i.e. teleseismic) shear wave, the value of AVs for each composition considered is not only significantly smaller than the maximum recorded but it is also smaller than the equivalent and azimuthally independent absolute AVp value (Fig. 11b). The magnitude of the vertical AVs also decreases with increasing mafic (pyroxene) content, although a slight increase may be significant at the change from effectively felsic to effectively mafic granulite compositions. The polarization direction of the fast (teleseismic) shear wave (i.e. Vs1P) is essentially constant ‘north–east–southwest’ for all compositions except for the slight increase in AVs values, where it is ‘east–west’. The behaviours of the vertical (teleseismic) AVs and Vs1P clearly reflect the increasing influence of pyroxene and suggest that mafic and ultramafic lithologies with (sub-) horizontal layering may exhibit little recognizable and/or interpretable shear-wave splitting anisotropy (e.g. see Díaz-Azpiroz et al. 2011).

Discussion

While recent studies suggest that crustal deformation is distinguishable via seismic profiling using velocity and/or anisotropy (e.g. Meltzer et al. 2001; Meltzer & Christensen 2001; Chlapacova et al. 2003; Brown et al. 2009; Moschetti et al. 2010), the source(s) of these seismic properties must be constrained. In the ductile continental crust, the usual source is the CPO characteristics of the rocks through which the seismic waves travel. It appears to be tacitly assumed that CPO not only indicates foliation but is also mimicked by the seismic symmetry (e.g. Siegesmund et al. 1989; Okaya & Christensen 2002; Kitamura 2006; Meissner et al. 2006; Barberini et al. 2007). Thus, micas are generally regarded as controlling the seismic properties of much of the ductile continental crust (e.g. Vernik & Liu 1997; Meltzer & Christensen 2001; Nishizawa & Yoshino 2001; Mahan 2006; Valcke et al. 2006; Lloyd et al. 2009). However, there is little evidence for meta-pelitic layers in deep continental crust as increasing Vp values with depth are interpreted as indicating increasing mafic component (e.g. Rudnick & Fountain 1999; Rudnick & Gao 2003). Furthermore, the present contribution has shown (i.e. Figs 1–8) that while relationships exist between mineralogy, CPO, deformation and seismic symmetry, the precise natures need to be established rigorously, usually for each geodynamic situation.

Figures 9–11 summarized these results and initially considered the potential origins of the seismic properties of the middle and lower ductile continental crust, which form the basis for many tectonic and/or geodynamic interpretations. The simple questions to be posed/answered when considering the seismic properties of the ductile continental crust are therefore: (1) what seismic velocity and/or anisotropy is/are observed/required; (2) what mineralogy/composition and/or CPO/deformation state is/are observed/required; and/or (3) what tectonic/geodynamic setting(s) explain(s) the seismic properties and/or geology observed? The rest of this discussion considers these questions based on the results presented in this study and provides some caveats for the accuracy and reliability of some current geodynamic models based on seismic profiling of the ductile (middle and lower) continental crust.

Seismic velocity (Vp) profiling

The typical mica modal contents of most rocks is <30% and alone cannot account for observed mid-crustal Vp values of 6.2–6.8 km/s, particularly if foliation/layering is (sub-) horizontal (e.g. Fig. 9a, b). Consequently, other faster common rock-forming minerals (such as feldspars) must make the most significant contributions (e.g. Figs 1, 2, 10a & 11a). Micas therefore cannot be regarded as being responsible for the Vp values observed in the ductile continental crust. Furthermore, while micas are amongst the most significant and sensitive foliation-forming minerals, their VTI characteristics make them insensitive to most deformation states (e.g. Fig. 8a). Indeed, it appears that micas are capable only of distinguishing constrictional
deformations, ironically due to the lack of foliation development. Exceptional care must therefore be taken when attempting to infer tectonic states from micaceous rocks, particularly where the orientation and/or number of any foliation(s) is/are unknown.

In contrast to micas, the wide range of amphibole modal contents possible naturally (i.e. up to and exceeding 65%) could explain observed Vp values in not only the middle but also much of the lower continental crust (e.g. Figs 9c & 10a). Indeed, Vp values in excess of 7 km/s and regarded as indicative of the lowermost continental crust can be explained by hydrous rocks with very high amphibole contents (i.e. so-called ‘hornblendites’) and subvertical foliation(s). However, as with micas, amphiboles form foliation/layering relatively easily and (sub-)horizontally oriented foliation/layering acts to reduce Vp values significantly (e.g. Figs 9c & 10a). Nevertheless, amphiboles (unlike micas) are sensitive to most deformation states due to their lack of VTI characteristics (e.g. Fig. 8b). The Vp characteristics of most of the ductile continental crust can therefore be explained by amphiboles alone, but conditions must be regarded as being hydrous.

The highest Vp values recognized are provided by pyroxenes (e.g. Figs 9d & 11a). Indeed, so-called ‘pyroxenites’ are capable of exhibiting velocities of c. 8 km/s, perhaps associated more usually with upper mantle lithologies (e.g. Ben Ismail & Mainprice 1998). Even relatively low pyroxene modal contents can explain Vp values associated with the middle continental crust, while pyroxene granulite compositions readily account for most lower continental crustal values (e.g. Figs 9a & 11b). Although (sub-)horizontally oriented foliation/layering will again act to reduce Vp, values are likely to remain sufficiently high to explain most middle and especially lower crustal observations. The Vp characteristics of most of the ductile continental crust can therefore be explained by pyroxenites alone, but conditions must be regarded as being anhydrous.

In summary, it is unlikely that seismic profiling observations based on Vp characteristics alone are capable of providing accurate and/or reliable interpretations of the middle or lower ductile continental crust. Both amphiboles and pyroxenites yield acceptable Vp values but micas do not and require significant contribution from other common rock-forming mineral phases (e.g. feldspars).

Seismic anisotropy (AVp, AVs) profiling

Both mica-dominated felsic and amphibole-dominated mafic lithologies are capable of generating the levels of AVp and AVs recognized naturally (e.g. Figs 9a–c & 10). In detail, micas and amphiboles contribute differently to whole-rock anisotropy. In felsic rocks, relatively low (i.e. <30%) modal mica contents are offset by relatively high mica single-crystal elastic anisotropy (Fig. 1). In mafic rocks, relatively high (>50%) modal amphibole contents offset relatively low amphibole single-crystal elastic anisotropy. However, the impact of micas on both AVp and AVs appears to be more significant overall (compare Figs 9a & 9c).

In contrast to micas and amphiboles, pyroxenes do not appear to contribute significantly to whole-rock anisotropy (e.g. Figs 9d & 11). This behaviour is clearly related to the relatively low single-crystal elastic anisotropy of pyroxenes (Fig. 1).

In summary, significant AVp and AVs values observed in the ductile middle to lower continental crust are due to either mica (felsic) and/or amphibole (mafic hydrous) lithologies. Furthermore, relatively low or intermediate values of anisotropy could also be due to pyroxene (mafic anhydrous) lithologies. It will therefore be difficult and/or impossible to distinguish between contrasting felsic and mafic compositions and/or conditions using seismic anisotropy profiling observations alone.

Seismic shear-wave splitting polarization (AVs, Vs1P) profiling

AVs values measured normal to foliation and/or compositional layering are typically significantly lower than the maximum AVs values possible (e.g. Figs 5 & 6) due to the composition and intrinsic properties of the single-crystal elastic anisotropy and whole-rock CPO (e.g. Figs 1 & 8). In addition, the polarization direction of the fast shear wave (i.e. Vs1P) may also vary with shear-wave propagation direction, which similarly depends on composition, single-crystal elastic anisotropy and CPO. Thus, variations in AVs–Vs1P (e.g. Figs 10 & 11) may not necessarily reflect different kinematics, as is often assumed in many geodynamic interpretations of seismic profiling data (e.g. Ozacar & Zandt 2004; Shapiro et al. 2004; Sherrington et al. 2004; Schulte-Pelkum et al. 2005). For example, if the lower continental crust comprises layered mafic lithologies (whether amphibole or pyroxene dominated) and the layering is oriented (sub-)horizontally as is often assumed (e.g. Rudnick & Fountain 1999), it is likely to exhibit only low shear-wave splitting anisotropy and may even appear essentially isotropic irrespective of its actual composition and deformation state (e.g. see Díaz-Azpiroz et al. 2011).

Seismic properties of ductile continental crust: an example

Recently, Moschetti et al. (2010) used ambient noise tomography to argue for strong, deep
(middle-to-lower) crustal radial seismic anisotropy beneath the western USA, confined mainly to geological provinces that have undergone significant extension in the last 65 Ma. They consider that the coincidence of crustal radial anisotropy with extensional provinces suggests that the anisotropy results from the CPO of anisotropic crustal minerals caused by extensional deformation. Consequently, their observations provide support for the hypothesis that the deep crust within these regions has undergone widespread and relatively uniform strain in response to crustal thinning and extension. We now consider the results of Moschetti et al. (2010) in terms of the observations presented in this contribution.

In general, the seismic results of Moschetti et al. (2010) recognize seismic anisotropy in the middle-to-lower crust and hence support our basic conclusion that the ductile continental crust can contribute significantly to the overall seismic anisotropy detected in the Earth. However, can their seismic results be interpreted geologically by the observations and relationships established in the present study? To attempt to answer this question we have incorporated the best-fit results of Moschetti et al. (2010, supplementary fig. 6a, b), which predict AVs of $c$. 5%, into our observations on the impact of different modal contents of mica (biotite), amphibole (hornblende) and pyroxene (hypersthene) on seismic properties (i.e. Figs 9–11). For the purposes of this comparison, these figures have been amended to include the maximum and minimum in the CPO-derived Vs1 and Vs2. To comply with the analysis presented by Moschetti et al. (2010), these are termed $V_{S1}$ and $V_{SH}$ here to represent a horizontally propagating shear wave split into vertical and horizontal components (Fig. 12).

According to the results presented previously (Fig. 9), felsic lithologies with mica contents of $<18\%$ are required to explain the middle crust Vs values indicated by Moschetti et al. (2010) while their AVs of $c$. 5% require $<5\%$ modal mica (Fig. 12a). However, only the latter composition can result in typical middle crustal Vp values (e.g. Rudnick & Fountain 1995). Felsic lithologies with mica contents of up to 18% require the presence of one or more seismically ‘fast’ minerals, that do not impact on anisotropy, to achieve middle crustal Vp values. The lower crustal Vs and AVs values indicated by Moschetti et al. (2010) cannot be achieved by variation in modal mica content in the felsic lithology considered here (Fig. 12a). In addition, micas cannot explain the overall results indicated by Moschetti et al. (2010) due to their VTI characteristics, which force isotropy in the radial plane for flattening and plane strain (simple-shear) deformations (e.g. Fig. 8a). Consequently, any anisotropy observed in the radial plane must be due to other minerals, which may be possible for low biotite contents.

While hydrous mafic lithologies with amphibole contents of $27–72\%$ (Fig. 10) readily explain the lower crustal Vs values indicated by Moschetti et al. (2010), even the lowest amphibole contents yield shear-wave velocities that are too high for their middle crust (Fig. 12b). Notwithstanding these comparisons, increasing amphibole content can account for the Vp values expected for the middle and lower crust (e.g. Rudnick & Fountain 1995). The AVs value of $c$. 5% predicted by Moschetti et al. (2010) can be satisfied by amphibole contents of 35–40%, which are compatible with both middle and lower crustal Vp values and the Vs values predicted by Moschetti et al. (2010) for their lower crust (Fig. 12b). In addition, amphiboles exhibit radial VTI characteristics for flattening type deformations but, for deformations where $K \approx 1$ (e.g. plane strain, simple shear, etc.), they exhibit slight radial anisotropy. Any anisotropy observed in the radial plane must therefore be due to either other minerals for flattening type deformations, which implies relatively low amphibole contents, or implies some type of shear deformation.

Anhydrous mafic lithologies with pyroxene contents of $<18\%$ and 17–37% explain the Vs values of Moschetti et al. (2010) for the middle and lower crust, respectively (Fig. 12c). However, Vp values for the former are less than expected for the middle crust while for the latter Vp is only that expected for the middle crust (e.g. Rudnick & Fountain 1995). Furthermore, AVs values are considerably higher than the 5% predicted by Moschetti et al. (2010), probably due to the lack of impact of pyroxene.

The ratio Vp/Vs is often used seismologically to characterize rock types and, in particular, to recognize hot rocks and/or the presence of melt. Moschetti et al. (2010) also calculated the variation in this parameter with depth in their seismic analyses but observed little change (Fig. 12 insets). In terms of the CPO-derived seismic properties, the ratio Vp/Vs can be defined either by Vp-max/Vs2-min to give a maximum, or by Vp-min/Vs1-max to give a minimum value. A range of Vp/Vs values can therefore be plotted with variation in, for example, modal content of a specific mineral (Fig. 12 insets). The ranges of Vp/Vs expand significantly with increasing modal content of, particularly, mica in felsic lithologies and amphibole in hydrous mafic lithologies (Fig. 12a, b insets). In contrast, the increasing modal content of pyroxene in anhydrous mafic lithologies results in a contraction of this range (Fig. 12c inset). Nevertheless, the ranges predicted from the CPO-derived seismic properties generally bracket the values.
Fig. 12.
suggested by Moschetti et al. (2010), except for pyroxene contents in excess of 80%.

Based on the observations presented in this contribution, we can therefore explain geologically the seismic results described by Moschetti et al. (2010) in terms of a dominantly amphibolitic and hence hydrous middle/lower continental crust beneath the current western USA. A composition of c. 40% amphibole and c. 60% felsic minerals (e.g. plagioclase and quartz) is compatible with our results. Furthermore, the extensional deformation indicated is due to horizontal (simple?) shear rather than vertical flattening, accommodated by the development of CPO in the amphibole to produce the observed radial crustal anisotropy of c. 5%.

Seismic profiling strategy for the ductile continental crust

The observations made and experiences gained in this contribution have led us to suggest the following strategy for in situ seismic profiling of the ductile continental crust. Essentially, there is one basic question that needs to be considered: what seismic velocities and/or anisotropies are observed and/or needed to explain a particular geodynamic setting? To answer this question it is important to make use of as much seismic information as possible as individual parameters (e.g. $V_p$, $V_s$, $AV_p$, $AV_s$, etc.) are sensitive to different geological constraints and hence provide information on different aspects of the geodynamical setting, as the following considerations illustrate.

Relatively low mica modal contents are capable of generating strong mica CPO in felsic rocks, resulting in relatively large seismic anisotropy but relatively low P-wave velocity. Thus, anisotropic felsic rocks with typical middle crustal P-wave velocities must consist of mica(s) and seismically faster minerals. However, if any associated foliation is oriented normal to the seismic wave propagation direction, both anisotropy and velocity will be minimized. Nevertheless, due to the VTI characteristics of mica(s) (which tend to dominate seismic property distributions in three dimensions), it will be difficult to distinguish specific types of deformation (except constriction) unless the other minerals are able to impart significant modifications.

To generate similar seismic anisotropy in mafic rocks as micaceous felsic rocks requires large but not unrealistic amphibole modal contents, which can also account for most middle and lower crustal P-wave velocities. Such lithologies imply hydrous conditions. Again, foliation orientation is significant in terms of the velocity and particularly anisotropy detected. The non-VTI characteristics of amphibole mean that different types of deformation (e.g. flattening, simple shear, constriction) can be distinguished.

The fastest P-wave velocities are associated with pyroxene-dominated lithologies which can account for velocities associated with both the lower crust and upper mantle, particularly when garnet is also present (see Brown et al. 2009). Such situations imply anhydrous conditions. However, it appears that such lithologies tend to exhibit relatively low anisotropy (whether normal or parallel to foliation), especially when garnetiferous. Although in principal the non-VTI characteristics of pyroxene mean that different types of deformation can be distinguished, in practice this may prove difficult due to the lack of detail in the seismic property distributions.

Conclusions

Results of rock- and fabric-recipe modelling using representative rock samples suggest that the seismic properties of the middle and lower continental crust depend on CPO and deformation as well as composition, while reliable interpretation of seismic survey data should incorporate as many seismic properties (i.e. $V_p$, $V_p$, $AV$, $V_s$, etc.) as possible. Crustal $AV$s is controlled by the dominant rock fabric-forming mineral: micas provide the most significant values, even at low concentrations, and amphiboles are significantly weaker except at higher concentrations. As lithology and anisotropy vary with depth, AVs can have a significant crustal component (e.g. steep, pervasive coaxial mica fabrics). Micas do not contribute significantly to $V_p$, however; observed $V_p$ and AVs values imply

Fig. 12. Explanation of the seismic results of Moschetti et al. (2010) in terms of the potential geology of the middle-to-lower crust beneath the western USA using observations presented in this contribution (see Figs 9–11) amended to include the CPO-derived shear-wave velocities. The black boxes in the velocity graphs represent the splitting of horizontally propagating shear waves into vertical and horizontal components, while in the anisotropy graphs they represent the best estimate AVs as reported by Moschetti et al. (2010, fig. 6a, b) for their best-fitting results, plotted in order to intercept with the respective CPO-derived values. The inset in each part compares their $V_p$/Vs ratio with the ranges predicted via CPO (NB minor inflection points indicate change from upper, middle and lower crust and mantle). (a) Felsic lithologies (varying modal biotite content); (b) hydrous mafic lithologies (varying modal amphibole content); and (c) anhydrous mafic lithologies (varying modal pyroxene content).
the middle/lower crust is dominated by mafic lithologies, including ‘amphibolites’. Seismic symmetry is crucial in distinguishing strain type. Micas exhibit VTI and are unlikely to distinguish either radial deformation typical of flattening strains (i.e. $X \sim Y \gg Z$; $K \rightarrow 0$) or ductile deformation typical of simple-shear zones (i.e. $X > Y > Z$; $K \sim 1$), where multiple fabrics may also interfere. Amphiboles exhibit ‘orthorhombic’ symmetry and distinguish potentially all common strain types, providing more sensitive tests of anisotropy-derived tectonic models (e.g. anisotropic lower crust with high Vp values can be explained by foliated amphibolites, although pyroxene granulites with only minor biotite content can achieve similar impact). These results pose significant constraints for many currently extant seismically based geodynamic models.

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