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Tectonophysics 416 (2006) 81–99

TECTONOPHYSICS

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Seismic lamination and anisotropy of the Lower Continental Crust

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Accepted 28 November 2005

Abstract

Seismic lamination in the lower crust associated with marked anisotropy has been observed at various locations. Three of these locations were investigated by specially designed experiments in the near vertical and in the wide-angle range, that is the Urach and the Black Forrest area, both belonging to the Moldanubian, a collapsed Variscan terrane in southern Germany, and in the Donbas Basin, a rift inside the East European (Ukrainian) craton. In these three cases, a firm relationship between lower crust seismic lamination and anisotropy is found. There are more cases of lower-crustal lamination and anisotropy, e.g. from the Basin and Range province (western US) and from central Tibet, not revealed by seismic wide-angle measurements, but by teleseismic receiver function studies with a P–S conversion at the Moho. Other cases of lamination and anisotropy are from exhumed lower crustal rocks in Calabria (southern Italy), and Val Sesia and Val Strona (Ivrea area, Northern Italy). We demonstrate that rocks in the lower continental crust, apart from differing in composition, differ from the upper mantle both in terms of seismic lamination (observed in the near-vertical range) and in the type of anisotropy. Compared to upper mantle rocks exhibiting mainly orthorhombic symmetry, the symmetry of the rocks constituting the lower crust is either axial or orthorhombic and basically a result of preferred crystallographic orientation of major minerals (biotite, muscovite, hornblende). We argue that the generation of seismic lamination and anisotropy in the lower crust is a consequence of the same tectonic process, that is, ductile deformation in a warm and low-viscosity lower crust. This process takes place preferably in areas of extension. Heterogeneous rock units are formed that are generally felsic in composition, but that contain intercalations of mafic intrusions. The latter have acted as heat sources and provide the necessary seismic impedance contrasts. The observed seismic anisotropy is attributed to lattice preferred orientation (LPO) of major minerals, in particular of mica and hornblende, but also of olivine. A transversely isotropic symmetry system, such as expected for sub-horizontal layering, is found in only half of the field studies. Azimuthal anisotropy is encountered in the rest of the cases. This indicates differences in the horizontal components of tectonic strain, which finally give rise to differences in the evolution of the rock fabric.

Keywords: Reflection seismics; Seismic lamination and anisotropy; Lower continental crust; Crust–mantle boundary

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1. Introduction

One of the most spectacular appearances of seismic reflections is the densely laminated reflectivity in the lower crust that is widely observed in the shallow crust of Phanerozoic extensional areas (Sadowiak and Wefer, 1990; Mooney and Meissner, 1992; Rey, 1995; Meissner and Rabbel, 1999). This reflectivity has been detected along many marine profiles in western Europe around the British Isles during the reflection programs BIRPS, starting in 1981, (British Institutions Reflection Profiling Syndicate) (Matthews and the BIRPS Group, 1990; Klemperer and Hobbs, 1991 and references

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0040-1951/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2005.11.013

therein), DEKORP in the German Variscides, (Meissner and Bortfeld, 1990 and references therein) and ECORS in the Paris Basin (Bois et al., 1986, 1987; Pinet et al., 1987). Strong lower-crustal reflectivity was later also found in parts of North America, for instance in the Basin and Range province, (Allmendinger et al., 1986; McCarthy and Thompson, 1988; Cook et al., 1997; Peng and Humphreys, 1997), and even in the thick compressed belts of Tibet (Ross et al., 2004; Huang et al., 2000; Sherrington et al., 2004), which show some extensional components of stress.

Among the many explanations, including multiple scatterers or fluids, a general tectono-thermal origin under stress and strain in a warm, ductile environment seems to be the most appropriate explanation (Mooney and Meissner, 1992; Meissner and Rabbel, 1999). Stretching and flow processes of heterogeneities, including mafic intrusions, are supposed to form long, sub-horizontal and therefore reflecting thin layers (“lamellae”), producing marked contrasts in seismic impedance. Scatterers and/or the presence of fractal inhomogeneities may also form some near-horizontal images (Emmerich, 1992; Hollinger et al., 1994).

However, the observed (ordered) reflectivity with continuous reflector lengths of more than 10 km or the missing “diffraction tails” are hard to explain. The presence of large amounts of fluids has also been suggested (Matthews and the BIRPS Group, 1990), but this explanation seems doubtful when considering several near-vertical experiments with P- and S-waves that show a comparable reflection strength, at least in the Black Forrest (Lueschen, 1999; Holbrook et al., 1992).

We think that stretching and ductile flow are the most important prerequisites for the generation of lamination and LPO-related-anisotropy in which the fast axes of anisotropic minerals (e.g. hornblende, muscovite, biotite) are aligned in the flow direction (Ribe, 1989; Savage, 1999; Park and Levin, 2002). We speculate that both processes – the formation of seismic lamination and anisotropy – are linked together, as suggested already by Pohl et al. (1999) and Meissner and Rabbel (1999). Both phenomena – lamination and anisotropy – should be frozen-in together during cooling (and modified or destroyed by new tectonic stresses). We will concentrate on three locations where this hypothesis can be tested, that is, where seismic lamination was observed in the lower crust and where complementing wide-angle investigations of seismic anisotropy were performed: (1) the Urach area and (2) the Black Forrest in the Variscan internides, and (3) the Donets Basin within the East-European craton.

Furthermore, we will briefly discuss two more locations showing both lamination and anisotropy, but it does not exclusively originate in the lower crust. These are the Basin and Range province in the western US, (Allmendinger et al., 1986, 1987; McNamara and Owens, 1993; Howie et al., 1991), and Central Tibet where tectonic escape is observed and independent investigation of lamination and anisotropy were carried out (Ross et al., 2004; Huang et al., 2000; Sherrington et al., 2004), and where crustal anisotropy was revealed using receiver function methods (Sherrington et al., 2004). In three more cases lamination and anisotropy of a former lower crust is inferred from petrological studies of exhumed lower crustal rocks now exposed at the surface (Weiss et al., 1999; Pohl et al., 1999).

Finally, we will briefly mention the eastern Alps where lamination and anisotropy are observed but here an additional anisotropy of the upper crust, caused by fault zones or foliation, may also contribute to the crustal anisotropy.

2. Main characteristics of lower-crust lamination

The terms “lamination” or “lamellae” have been used since the beginning of the 1980s, when the first land-based, near-vertical reflection experiments in Europe were conducted across the geothermal anomaly near Urach in the Moldanubian terrane in southern Germany (Bartelsen et al., 1982). The reflection patterns from these experiments always show strong reflectivity of the lower crust. These patterns were also observed in large parts of western Europe. Fig. 1 presents a typical profile SW of England across an extensional Mesozoic basin showing pronounced lower-crustal lamination (Warner, 1991; Cheadle et al., 1987). This reflection pattern is completely different from those recorded earlier in the USA during the COCORP program, which had already started in 1975 (Oliver, 1986, 1990; Brown et al., 1986).

Lower-crustal lamination, compared to the significantly lower reflectivity in the crystalline upper crust and the upper mantle, is considered a special type of continental reflectivity that contrasts with other reflectivity types like diffuse, fault- or convergence-related reflectivity, or special highly reflective zones at the base of the crust (McGeary, 1987; Sadowiak and Wefer, 1990; Meissner and Brown, 1991). Lower-crustal lamination is certainly based on the tectonic-rheological development of special areas (Mooney and Meissner, 1992). It seems to be concentrated in extensional areas, specifically in areas where the most recent tectonic event involved extension. This explains the lack of