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Age-differentiated subduction regime: An explanation of regional scale upper mantle differences beneath the Alps and the Variscides of Central Europe

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ABSTRACT

The upper mantle beneath the Alps and the Variscides of Central Europe has a varied seismic structure as a result of the accretionary and evolutionary processes that have shaped it. Natural earthquake data, the raypaths of which pass beneath these regions, have enabled the calculation of travel times out to 3000 km. The source-receiver geometry ensured there was broadband station coverage at offsets between 900 and 3000 km, enabling the detection of the appropriate upper mantle phases over an azimuthal span embracing the studied structures. The resulting data allowed us to model first order discontinuities to a depth of about 420 km. We have used modelling based on ray-tracing in a cylindrical coordinate system reflecting the geometry of the wave propagation medium. The data allow determination of the thickness of the upper mantle low velocity zone (LVZ) beneath the Alpine orogen. It appears to be thicker than beneath surrounding areas, with its upper 'lid' at a depth of about 90 km and its base, the 'Lehmann discontinuity', being depressed to 220 km. Such thickening of the LVZ is typical below young orogens. A seismic discontinuity at a depth of around 300 km, with the P-wave velocity increasing to 9 km/s, has been observed for all the sub-Alpine raypaths. We consider this discontinuity to have originated as a result of Alpine orogen subduction. This is responsible not only for changes in the thermal field as a result of transporting colder material to depths probably exceeding 200 km but also for delivering the necessary amounts of excess silica required for the coesite–stishovite phase transition. For rays passing beneath the Variscides, there is a scatter in travel times over the 8–15° distance range. However, the scattering does not indicate significant thickening of the LVZ as identified beneath the Alpine orogen, and the Lehmann discontinuity at the base of the LVZ does not exceed 200 km depth. Also, in contrast to the Alps, no high velocity phases are observed for a discontinuity near 300 km depth. This supports our contention that the 300-km discontinuity is a regional feature ascribed to the subduction regime beneath the younger orogen. For all azimuths from which structures beneath the Alps are illuminated, we clearly observe both the refraction as well as the reflection branch from the 410-km discontinuity.

1. Introduction

Finding the links between surface and deeper mantle processes is the focus of many geodynamic studies. It has been shown (Anderson, 2001; Dziewonski et al., 2010) that mechanisms responsible for heterogeneous structures at different mantle depths and scales can be coupled. The seismic wavefield generated in upper mantle structures is a rich source of information about the velocity distribution at depths inaccessible to direct measurement. The velocity field is a starting point for calculating other physical parameters of the medium such as density or temperature. The observation and joint interpretation of different parameter distributions can translate into a realistic petrological model thanks to recently improved technical facilities for producing ultra-high pressure and temperature conditions in the laboratory.

In upper mantle investigations, high magnitude earthquake data provide a unique opportunity for the calculation of travel-times over distances of a few thousand kilometres, a range normally outside the scope of wide-angle reflection/refraction experiments.

The images of the upper mantle presented in global reference models (such as PREM (Dziewonski and Anderson, 1981), AK135 (Kennett et al., 1995) or iPREF (Cammarano and Romanowicz, 2008) are highly averaged and do not generally reveal regional scale features. It is this regional scale that is the focus of this work. Our approach, based on solving the forward problem using raytracing theory, is independent of the choice of starting model. Seismic

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rays recorded in Central Europe provide the opportunity of studying upper mantle structures from beneath two adjacent regions that were formed during orogenic events separated in time by more than 300 My. The motivation for our work involved the desire to adopt active-source wide-angle seismic methods but applied to substantially longer profiles than the norm. The resulting seismic sections have been constructed from the rich set of natural earthquake data recorded on the European Broadband Seismic Network which has been significantly modernised in recent years. Using such an approach we have derived models down to depths of 500 km, inaccesible to active-source studies. Modelled 2-D velocity distributions and the geometry of identified seismic discontinuities form the basis for a discussion concerning the nature of the causative structures, so casting new light on the geodynamic evolution of the study volume.

2. The study volume – tectonic setting and current models

In this paper we analyse the seismic wavefield recorded from beneath two tectonically-differentiated units in Central Europe – the Alps and the Variscides. The surface boundary between the two orogens is identified in Fig. 1. The older Variscan units date back to Palaeozoic (Silurian to Permian) intense orogenic events which took place between 400 and 230 Ma. Since that period the orogen has been largely eroded (Franke, 2006). The younger Alpine orogen started to form in the Mesozoic (between the Jurassic and Cretaceous) about 150 My ago and is still subject to ongoing subduction processes (Agard and Lemoine, 2005; Diehl et al., 2009a,b).

The Alps are a prime example of a collisional orogen, their formation being directly related to the convergence of the Eurasian and Apulian–African–Arabian plates. A number of ancient ocean basins, including the Valais, Liguro-Piedmont and Neotethys, have been consumed during the associated subduction. The palaeogeographical reconstructions of the region have been widely discussed in the literature (Blundell et al., 1992; Channell and Kozur, 1997; Raumer et al., 2003; Cavazza et al., 2004; Schmid et al., 2004). The linear extent of the oceanic floor, subducted for over 100 My is estimated to have exceeded 800 km. Subducted material has mainly been incorporated into the mantle; however, the depth to which it has penetrated is the subject of speculation. Receiver

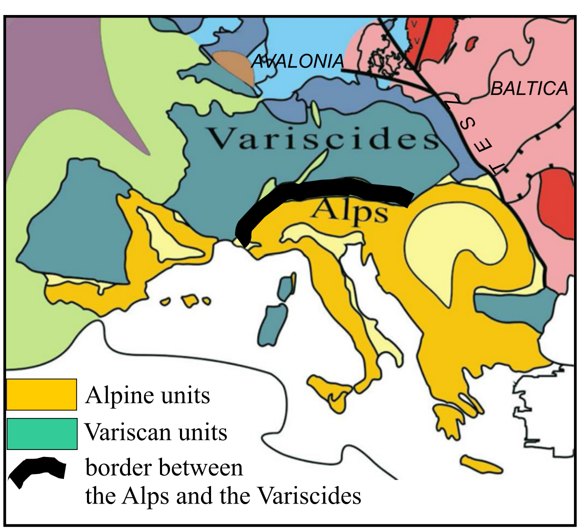

Fig. 1. Outline tectonic map of Central Europe (modified after Gee and Stephenson, 2006) with the bordering part of the studied orogens marked by a thick black line. Light blue – remnants of Avalonia. Pink – regions of Baltica craton affinity located east of the Trans European Suture Zone (TESZ) marked by a thin black line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

function studies of the mantle transition zone (Lombardi et al., 2009) image cold remnants accumulated at the 600 km discontinuity. In tomographic images (Piromallo and Morelli, 2003; Lippitsch et al., 2003; Schmid et al., 2008; Koulakov et al., 2009) distinct high velocity anomalies that extend to over 100 km in the upper mantle are interpreted as detached fragments of oceanic lithosphere sinking into the mantle. Only a small part of this lithosphere has been returned back to the surface forming ultra-high pressure metamorphic terranes spatially associated with ophiolitic fragments. These terranes contain metasediments including coesite – a high pressure polymorph of quartz – and eclogites tectonically juxtaposed with peridotites and deep-seated garnet peridotites (Green et al., 1997, 2000; Trommsdorff et al., 2000).

The Variscan crust is an assemblage of several terranes resulting from the fragmentation of Gondwana into a number of microplates, which subsequently docked into Avalonia and Baltica (see Fig. 1). The sequence of collision and subduction in Devonian and Carboniferous times gave rise to a geologically diverse orogen with two distinct subduction zones – along the border between the Moldanubian and Bohemian Massif, and in the region of tectonic sutures between the Armorican and Aquitaine-Cantabrian terranes (Dezes et al., 2004; Ziegler and Dezes, 2007). The closure of the Rheic and Saxothuringian oceans initiated subduction of lithospheric material in a N–S direction. The process was accompanied by high-pressure metamorphism and magmatism (Franke, 2006). Geodynamic scenarios explaining the tectonic formation of the orogen are widely presented (Berthelsen, 1992; Raumer et al., 2003; Franke, 2006; Ziegler and Dezes, 2006, 2007). The destruction of the orogen was a multi-stage process. While there is some evidence (Ziegler and Dezes, 2006) that the Variscides, during an intense stage of the orogeny had crustal roots reaching to 50–60 km as observed beneath the Alps today, at present they have no deep roots (Dezes and Ziegler, 2001; Grad and Tiira, 2009). A variety of refraction as well as reflection seismic profiling conducted in the region (Zeis et al., 1990; EUGEMI-Working-Group, 1990; Wever et al., 1990) identifies a relatively constant Moho depth in the range 25–35 km. The disappearance of the roots was partly caused by uplift and erosion. The orogenic processes resulted in a NE–SW orientation of the main tectonic blocks within Variscan Central Europe.

Multi-disciplinary projects have been conducted in Central Europe since the 1970s, focused primarily on obtaining integrated images of the lithosphere (Tesauro, 2009). The interpretation of gravimetric as well as heat flow measurements reveal different lithospheric physical parameters beneath the adjacent Alpine and Variscan orogens. The Alps are associated with a distinct, significantly lower Bouguer anomaly (Wybraniec et al., 1998). Geothermal models (Teasuro et al., 2009) show lower (by up to 200 °C) temperatures at a depth of 100 km below the Alps than beneath the surrounding Variscan units, can be explained by the presence of deeper lithospheric roots and subducted slabs in the Alpine upper mantle.

The most effective methods of subcrustal structure investigation are seismic refraction and reflection studies (e.g. ECORS (Roure et al., 1996), EGT (Blundell et al., 1992), NRP 20 (Pfiffner et al., 1997), TRANSALP (TRANSALP-Working–Group, 2001; Castellarin et al., 2006)), surface wave analysis (Panza et al., 1980), travel-time residual analysis (Babuška et al., 1990), and receiver function studies (Kummerow et al., 2004; Brückl, 2007). Numerous depth sections, with velocity anomalies calculated with respect to the assumed reference model, have been reported from P-wave (Spakman et al., 1993; Piromallo and Morelli, 2003; Diehl et al., 2009b; Koulakov et al., 2009), S-wave (Bijwaard et al., 1998; Koulakov et al., 2009) and teleseismic tomography (Lippitsch et al., 2003) analyses. The deepest models include the upper mantle transition zone (Geissler et al., 2008).