Tectonophysics 692 (2016) 58–73

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Mesozoic and Cenozoic evolution of the Central European lithosphere

T. Meier [a,*], R.A. Soomro [a,1], L. Viereck [b], S. Lebedev [c], J.H. Behrmann [d], C. Weidle [a], L. Cristiano [a], R. Hanemann [b]

[a] Christian-Albrechts University Kiel, Institute for Geosciences, Otto-Hahn-Platz 1, 24118 Kiel, Germany
[b] Friedrich-Schiller University Jena, Institute for Geosciences, Burgweg 11, 07749 Jena, Germany
[c] Dublin Institute for Advanced Studies, Geophysics Section, 5 Merrion Square, Dublin 2, Ireland
[d] GEOMAR, Helmholtz-Zentrum für Ozeanforschung Kiel, Dynamics of the ocean floor, Wischhofstrasse 1-3, 24148 Kiel, Germany

ARTICLE INFO

Article history:
Received 30 January 2016
Received in revised form 21 July 2016
Accepted 12 September 2016
Available online 13 September 2016

Keywords:
Seismic tomography
Continental lithosphere
Lithosphere-asthenosphere boundary
Intraplate volcanism
Central Europe

ABSTRACT

The upper crust of central Europe preserves a mosaic of tectonic blocks brought together by the Caledonian and Variscan Orogenies. The lower crust, in contrast, appears to have undergone extensive reworking: the flat Moho across broad areas and the absence of contrasts in seismic properties across tectonic boundaries suggest that the Moho and lower crust are, effectively, younger than the upper crust. The evolution of the mantle lithosphere below the Moho has been particularly difficult to constrain. In this paper, we use seismic, geological and geochemical evidence to show that central Europe's mantle lithosphere has evolved continuously throughout the Mesozoic and Cenozoic Eras, with episodes of lithospheric thinning causing surface uplift and volcanism and lithospheric thickening – subsidence and sedimentation. High-resolution surface wave tomography reveals a strong spatial correlation between locations of recent basaltic volcanism and currently thin lithosphere. We infer that intraplate volcanism further back in the geological past is also an indication of lithospheric thinning at the time. The north-central Europe's lithosphere was, thus, thinned at the time of the Permian volcanism, with its subsequent, Post-Permian cooling and thickening causing the subsidence and sedimentation in the North German and neighboring basins. This explains the presence of Permian volcanics atop presently thickened lithosphere. South of these basins, lithospheric thinning (evidenced by seismic data) is associated with the volcanism of the Central European Cenozoic Igneous Province and surface uplift. Thin lithosphere here also correlates spatially with high melting rates, high silica contents, high temperatures and shallow magma generation. This synthesis highlights the dynamic nature of the lithosphere-asthenosphere boundary beneath central Europe and, more generally, Phanerozoic continents. The boundary's depth varies in time; its deepening (lithospheric cooling and thickening) causes subsidence and sedimentation; its shallowing (lithospheric thinning by thermal erosion or delamination) is marked with uplift and intraplate volcanism.

1. Introduction

Central and western Europe is one of the parts of the world where modern geology developed as a science and, after centuries of scrutiny, the geological record across the region is very well documented. Plate tectonics has brought modern explanations for the formation of the European landmass in the Caledonian and Variscan Orogenies in the Paleozoic Era, and for active tectonics of the Africa-Eurasia convergence. Yet, a key piece of the puzzle is still missing. Whereas abundant evidence is available on the structure and evolution of the upper and middle crust, much less is known of the evolution of the deeper part of the plate, including the lower crust and, in particular, the mantle lithosphere. The deep evolution of the lithosphere and its interactions with the underlying asthenosphere are linked to the uplift and subsidence of the Earth's surface and to intraplate volcanism across central Europe. The difficulty in obtaining conclusive observational evidence, however, has meant that both the deep lithospheric evolution and its effect on surface tectonics and volcanism remain uncertain.

The lithosphere is the mechanically strong, outer layer of the Earth that makes up the tectonic plates. It comprises the crust and the uppermost, coldest part of the mantle - the lithospheric mantle. The lithosphere coincides, roughly, with the Earth's upper thermal boundary layer, in which temperature is relatively low and increases with depth along steep conductive geotherms. The conductive geotherms reach the mantle adiabat near the bottom of the lithosphere. Further down, heat transfer is primarily by convection within the warm, mechanically weak sublithospheric mantle (the asthenosphere).

The thermal evolution of the lithosphere looks fairly simple beneath the oceans: it cools and thickens monotonically from its birth at mid-ocean ridges to its ultimate subduction into the deep mantle at subduction zones, as seen clearly in recent tomographic models (e.g., Schaeffer and Lebedev, 2013). This dominant pattern is broken only by hotspots,

* Corresponding author.
E-mail address: meier@geophysik.uni-kiel.de (T. Meier).
[1] Now Seismic Studies Programme, Nilore, Islamabad 4000, Pakistan.

http://dx.doi.org/10.1016/j.tecto.2016.09.016
0040-1951/

which re-heat the oceanic lithosphere as it passes over them. After passing a hotspot, however, the plate would normally resume the cooling and thickening process.

There is continuing debate on whether the thickness of the oceanic lithosphere reaches a maximum at around 80 m.y. of the lithospheric age (the "plate model") or whether, instead, plate thickening according to the "half-space cooling model" (e.g., Davis and Lister, 1974; McKenzie et al., 2005) continues until the age of the oldest oceans on Earth today. The apparent lack of heat-flow dependence on the lithospheric age for old oceans (>80 Myr) and the flattening of the old oceans' bathymetry are evidence for the plate model (e.g., Stein and Stein, 1992, 2015). Yet, depth profiles of shear velocity and azimuthal anisotropy beneath the oceans appear to evolve with the seafloor age following the half-space cooling model, according to recent tomographic models (e.g., Becker et al., 2014; Schaeffer et al., 2016). In any case, it is clear that the oceanic lithosphere, hotspots aside, cools and thickens at least until 80 Myr of age, and then it either remains equally cold and thick or may continue to cool and thicken further.

Compared to oceanic lithosphere, continental lithosphere is characterized by much greater complexity in its structure and evolution, owing, in part, to its much greater range of ages. The oldest ocean floor within today's major ocean basins is Jurassic (around 180 Ma in the western Pacific), and the oldest preserved in-situ oceanic crust may be a remnant of the Neotethys Ocean beneath the Ionian Sea and the east Mediterranean basin, still only Triassic in age (230–270 Ma) (Müller et al., 2008). In contrast, the oldest intact fragments of continental crust are >4 billion years old (Bowring and Williams, 1999), and it is the Archean cratons (>2.5 Ga in age) that form the cores of today's continents. The global igneous record shows pronounced continental crust age peaks at 2.7 and 1.9 Ga, with some compilations suggesting another peak at 1.2 Ga (e.g., Condie, 1998; Hawkesworth et al., 2010). This record may not represent the true rates of crustal generation due to preservation artefacts (e.g. Gurnis and Davies, 1986) but it is clear that the evolution of the continental lithosphere measures >3 billions of years.

A natural consequence of the cooling of the lithosphere at the Earth's surface is that it will grow in thickness, up to a point when its bottom portion becomes unstable and sinks into the underlying mantle (Bird, 1979). Mantle lithosphere beneath Archean cratons is compositionally buoyant due to its depletion in basaltic components (e.g., Jordan, 1975, 1988). For this reason, the lithosphere beneath cratons can cool and grow to a greater thickness than elsewhere (although it can be partly rejuvenated and eroded: Foley, 2008; Legendre et al., 2012). In global and continent-scale seismic tomography models, cratons stand out as the most prominent high-velocity anomalies down to 200–250 km depths, which reflects their coldest and thickest lithosphere (Debayle and Ricard, 2012; French et al., 2013; Schaeffer and Lebedev, 2015).

Phanerozoic continental lithosphere, in contrast, never reaches thicknesses comparable to that of the cratons. Density of the Phanerozoic subcontinental lithospheric mantle (SCLM in the following) is higher than that of the Archean SCLM (at the same pressure and temperature), limiting the maximum Phanerozoic lithospheric thickness to about 150 km (Poudjom Djomani et al., 2001).

Like oceanic lithospheric mantle, the SCLM can also be thermally eroded; it then cools and thickens again. These processes lead to and are manifested by tectonic and magmatic consequences at the Earth's surface. Thermal erosion and thinning of the SCLM are accompanied by uplift and magmatism, whereas cooling of the lithosphere causes subsidence and development of basins (e.g., Poudjom Djomani et al., 2001). Stretching of the lithosphere can cause passive upwelling of the asthenospheric mantle, also followed by subsidence due to cooling (McKenzie, 1978). The thickening of the SCLM, however, is limited by delamination (Bird, 1979). Phanerozoic SCLM shows pronounced lateral variations, even when relatively stable, that is, not in immediate proximity to active orogens (e.g. Cloetingh et al., 2007; Legendre et al., 2012). This is a manifestation of dynamic processes involving the SCLM, the lithosphere-asthenosphere boundary (LAB), and the asthenosphere. Although these processes are likely to have major effects on continental tectonics and intraplate volcanism, they are still poorly understood.

Phanerozoic central Europe is a very suitable location to study these processes. Its lithosphere has been amalgamated by a series of Phanerozoic continent-continent collisions of Gondwana-derived terranes during the Caledonian and Variscan orogenies (e.g. Franke and Oncken, 1990; Berthelsen, 1992; Pharaoh, 1999; Thybo et al., 2002; Franke, 2006). The subsequent episodes of intraplate volcanism and sedimentary-basin development (e.g. Ziegler, 1990; Scheck and Bayer, 1999; van Wees et al., 2000; Ziegler and Dèzes, 2006; Lustrino and Wilson, 2007; Torsvik et al., 2008) are indications for the rejuvenation and cooling of the SCLM, respectively (as we discuss in detail in the following). The seismic properties of the crust in central Europe have been studied extensively (e.g. EUGENO-S working group, 1988; Meissner and Bortfeld, 1990; BABEL Working Group, 1993; Rabbel et al., 1995; MONA LISA Working Group, 1997; Grad et al., 2005). R. Meissner – to whom this special volume is dedicated - initiated and was involved in a number of deep seismic soundings of the crust in central Europe. The major findings of these initiatives are that (1) the crust is relatively thin (<35 km), most of it with a rather uniform thickness of 28 km to 32 km, (2) average crustal seismic velocities are rather low, (3) no expressions of terrane boundaries can be found in the lower crust, and (4) there is widespread reflectivity in the lower crust (Meissner et al., 1991; Meissner and Tanner, 1993; Meissner, 1999; Meissner et al., 2006; Artemieva and Meissner, 2012). From these observations, Meissner and co-workers inferred that the recent location of the crust-mantle boundary (Moho) in the area is younger than the tectonic age of the brittle upper crust, implying that the lower crust has been deformed during or after the Variscan orogeny.

In the northern part of the Variscan orogenic belt, basins formed in the Lower Permian (Rotliegend), with differential tectonic movements in the crust coming to a standstill in the Middle Permian (e.g. van Wees et al., 2000). The central European lithosphere has been further affected by the Permian volcanic event with a peak activity at about 290 Ma (Torsvik et al., 2008). There is evidence for widespread volcanic activity, especially in the Permian basins south of the East European Craton (EEC, Ziegler, 1990). It was followed by Mesozoic basin development in central Europe and the southern North Sea (e.g. Ziegler, 1990), with wide areas of epicontinental platform sedimentation. Van Wees et al. (2000) concluded that cooling of the lithosphere after thermal erosion in the Permian played a major role for the basin development. The sedimentation record is punctuated in many places, and comprises alternations of shallow water clastics, platform and basin carbonates, and occurrences of evaporites, mainly in the Middle and Upper Triassic. The Mesozoic sediments are unconformably superposed on Lower Permian (Rotliegend) clastics forming post-orogenic molasse-type deposits of considerable thickness in confined basins, and/or Upper Permian (Zechstein) evaporites and associated mudstones. In the Cenozoic, large areas in the south of central Europe were above sea level, but in Northern Germany and the North Sea subsidence produced basins with sedimentary fills more than three kilometers thick, mainly fine to coarse clastics. Further south and west, basin formation and subsidence in the Cenozoic are intricately connected to the European Cenozoic Rift System (e.g. Dèzes et al., 2004), which is made up of the Limagne, Bresse, Upper Rhine, Lower Rhine and Eger Graben structures, to name the most important ones.

There are only a few locations of Mesozoic volcanism south of the EEC and in central Europe, the volcanic field of Delitzsch-Bitterfeld and of the Northern Upper Rhine Graben (Odenwald, Sprendlinger Horst) (Schmitt et al., 2007; Krüger et al., 2013). But there is widespread Cenozoic volcanism in central Europe. Numerous intraplate volcanic fields stretch broadly parallel to the Alpine front between the Eifel (Germany) and Silesia (Poland) and form the northern E–W oriented zone of the Central European Cenozoic Igneous Province (CECIP, Wimmenauer, 1974; Wedepohl and Baumann, 1999; Lustrino and Wilson, 2007). As