Earth and Planetary Science Letters 397 (2014) 42–56

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Alpine lithosphere slab rollback causing lower crustal seismicity in northern foreland

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ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 29 March 2014
Accepted 1 April 2014
Available online 6 May 2014
Editor: P. Shearer

Keywords:
lower crustal earthquakes
northern Alpine foreland
slab rollback
stress transfer
high-precision earthquake locations

ABSTRACT

Beneath the northern foreland of the Central Alps deep crustal earthquakes up to magnitude 4 regularly occur in the continental lithosphere. At 20 km to 30 km depths, where most of these earthquakes are located, temperatures above 450 °C are expected. This leads to a more ductile rheology of the lower continental crust. To better understand occurrence and underlying processes of these unusual earthquakes, we homogenize and improve hypocenter locations of events in the period 1984 to 2012 using a high-precision multi-phase earthquake location method in combination with a reliable three-dimensional P-wave velocity model of the crust and uppermost mantle. With the new approach, the average uncertainty in focal depth of well-locatable earthquakes is less than ±1 km. The homogeneously relocated hypocenters suggest a relatively uniform depth distribution throughout the lower crust. In agreement with previous studies, seismicity is entirely restricted to the crust and no evidence for seismicity in the mantle lithosphere beneath the northern Central Alpine foreland was found. The geographical distribution of lower crustal earthquakes in the foreland correlates remarkably well with the lateral extent of the European slab beneath the Central Alps where it is still attached to the European lithosphere. In addition, the directions of extensional axes derived from focal mechanisms of the deep crustal earthquakes are predominantly parallel to the Alpine front. This consistency of extensional axes can be interpreted as the result of the transferred buoyancy force of the lower crust in the subduction, transformed to a compressional force in the foreland perpendicular to the Alpine front. Existing 2-D thermo-mechanical models predict such viscous bending and stress transfer to the foreland. In our proposed model, the anomalously deep crustal seismicity is driven by stresses transferred into the foreland interrelated with the exhumation of the crust form the orogenic root caused by the rollback of the European lithosphere.

1. Introduction

In the northern Alpine foreland of Switzerland the peculiar occurrence of lower crustal earthquakes in the continental European lithosphere has long been observed and intensively discussed (Deichmann and Rybach, 1989; Deichmann, 1992; Kissling et al., 2006a; Meissner and Kern, 2008). In February 2012, a magnitude 4.2 earthquake located just above the crust-mantle boundary (Moho) at 32 km depth resumed the discussion about the origin of the lower crustal seismicity in the foreland of the Alps. Since 1984 more than 470 earthquakes were located in the lower crust within 15 km of the Moho with an average local magnitude of 2 and a maximum magnitude of ML 4.2. These deep crustal earthquakes are concentrated in the northern foreland of the Central Alps and are absent south of the Alpine front (Deichmann et al., 1999). Beneath the northern foreland of the Western and Eastern Alps little evidence for the occurrence of lower crustal seismicity exists (Fig. 1). Although most of the lower crustal earthquakes are relatively small events (ML $\leq$ 2), their occurrence and spatial distribution give important insights into the rheologic and dynamic processes of the European lithosphere, engaged in the Alpine continent–continent collision. An understanding of the dynamic processes of the collision and its implication for the predominant tectonic stresses is essential for the seismic hazard assessment in the northern Alpine foreland.

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http://dx.doi.org/10.1016/j.epsl.2014.04.002

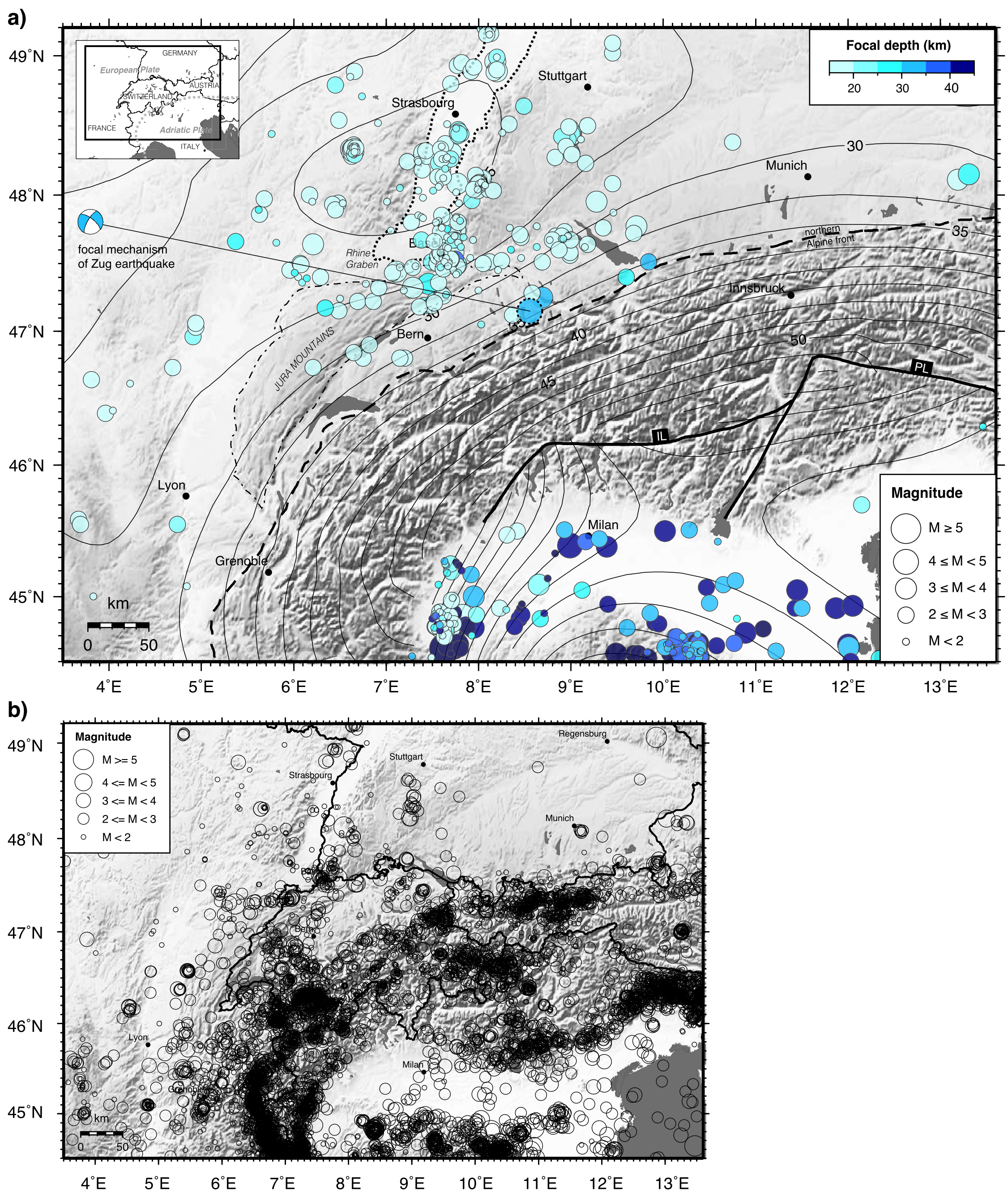

Fig. 1. Distribution of lower and upper crustal seismicity in the Alpine region as reported by the EMSC catalog for the period of 1998 to 2011. (a) Lower crustal seismicity: Earthquakes located within 15 km of the Moho are shown as circles with color indicating focal depth. The hypocenter location of the Zug earthquake on February 24, 2012 was determined by the Swiss Seismology Service (blue circle with dotted black outline). Contour lines indicate Moho depth (km) of the European respectively the Adriatic lithosphere (Wagner et al., 2012). The dotted line indicates the Rhine Graben, the dashed line the northern Alpine front (Helvetic front) and the dot-and-dashed line the extent of the Jura Mountains. IL: Insubric Line; PL: Periadriatic Line. (b) Corresponding upper crustal seismicity distribution (focal depth < 20 km and hypocenter distance to the Moho >15 km).

In the continental lithosphere the seismicity is generally confined to the brittle upper crust (Chen and Molnar, 1983; Chen, 1988; Maggi et al., 2000a; Scholz, 2002; Jackson, 2002). Earthquakes located in the lower crust like in the northern Alpine foreland or even in the mantle lithosphere outside subduction zones are rare. Besides the Alps such deep crustal earthquakes were recorded beneath the Tien Shan, northern India, East Africa, along the Oman Line (Maggi et al., 2000b) or Mongolia–Baikal (Jackson et al., 2008). From laboratory experiments, the key controlling factor, determining whether deformation of the lower continental crust is brittle or ductile is temperature (Chen et al., 2012). The supposed upper temperature limit for the brittle crust is around 300 – 400 °C and around 600 – 700 °C for the mantle (Chen et al., 2012). At 20 km to 30 km depths where most of the lower crustal earthquakes in the northern Alpine foreland occur, however, higher temperatures and a ductile rheology are expected (Deichmann and Rybach, 1989; Okaya et al., 1996). In contrast, Holliger and Levander (1994) and Meissner and Kern (2008) proposed a strong European lower crust based on a 'corset model' of thin mafic to ultramafic, sill-like intrusions to explain both the high-reflectivity of the laminated lower European crust and its seismicity. The distinct geographical distribution of these earthquakes and the origin