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Earthquakes in the lower crust under the Northern Alpine Foreland Basin: Seismological detection of active metamorphism?

J. Strehlau (1) and S. Stange (2)

(1) Inst. f. Geowissenschaften, Christian-Albrechts-Universität, 24098 Kiel, Germany (strehlau@pclab.ifg.uni-kiel.de), (2) Regierungspräsidium Freiburg, Landesamt f. Geologie, Rohstoffe u. Bergbau, 79104 Freiburg, Germany (stefan.stange@rpf.bwl.de)

About 130 small earthquakes (1994-2005, magnitudes up to 4.1) have been located under the Molasse Basin in the Swiss-German-Austrian border region, extending from Lake Zürich across Lake Constance to the Iller river. By including travel times of seismic waves reflected at the Moho, we can determine hypocenters with a relative depth accuracy of 3 km at best. The precision of hypocentral locations is limited by the average one-dimensional seismic velocity model and the approximate Moho topography based on several seismic profiles (e.g., EGT).

We resolve three distinct depth intervals: a seismogenic upper crust to 16 km, a middle crust with no or minimum seismicity from 16-20 km, and a seismogenic lower crust from 20 km to the Moho. The bottom edge of the upper zone remains at roughly the same depth across the foreland, whereas the top edge of the lower zone tends to follow the Moho as it deepens toward the Alps. The magnitude-frequency distribution has changed little since the onset of routine instrumental monitoring in this region (1975), but it is unknown whether the bimodal depth distribution represents a long-term characteristic of the Alpine foreland. No systematic variation of magnitude and seismicity rate with depth has been found.

A correlation of the focal depth distribution with the lithological column deduced from xenoliths collected in the Miocene Hegau volcanic province [1] indicates that the majority of deep crustal earthquakes occur in dominantly felsic material. Most of the xenoliths are metapelitic and granitic gneisses, but only a few have a granulitic spinel-pyroxene composition (pyribolites). Since the average P-wave velocity of the

deep Molasse crust is relatively low (6.0-6.7 km/s), except for the thin crust-mantle transition zone (ca. 7.2 km/s), one can conclude that mafic granulites do not represent a major component of the lower crust. It appears difficult, therefore, to explain the lower crustal seismicity in this region by a strong, mafic lower crust.

In an attempt to resolve the question as to whether the lower crust under the Molasse Basin may be anomalously cold, we have calculated steady-state conductive geotherms. Top model boundary conditions are derived from temperature measurements in exploration boreholes [2], and constant mantle heat flow has been assumed at the bottom margin (75 km depth). Temperature-dependent thermal conductivities and heat production estimates are reasonably well constrained by the Hegau xenoliths. Results for a model with a gently dipping crust show isotherms cutting across the Moho rather than following it. This effect is caused by the lateral increase of total heat production due to the greater crustal thickness under the Alps.

From a systematic variation of model parameters, Moho temperatures are estimated to range from $570 - 800\,^{\circ}\mathrm{C}$. Comparison with a metamorphic facies diagram indicates that the deep crustal earthquakes may occur at (or close to) the amphibolite-granulite transition. Since geologic and geodetic studies show that the Molasse Basin has undergone recent uplift and erosion [3-4], seismogenic faulting in the lower crust may be associated with retrograde metamorphism. However, many uncertainties and open questions remain. For example, transient thermal effects of Molasse sediment blanketing, Alpine nappe overthrusting, as well as deep-crustal fluid flow still need to be included in the models.

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