Earthquakes in the Lower Crust Under the Molasse Basin: Seismological Detection of Active Metamorphism?

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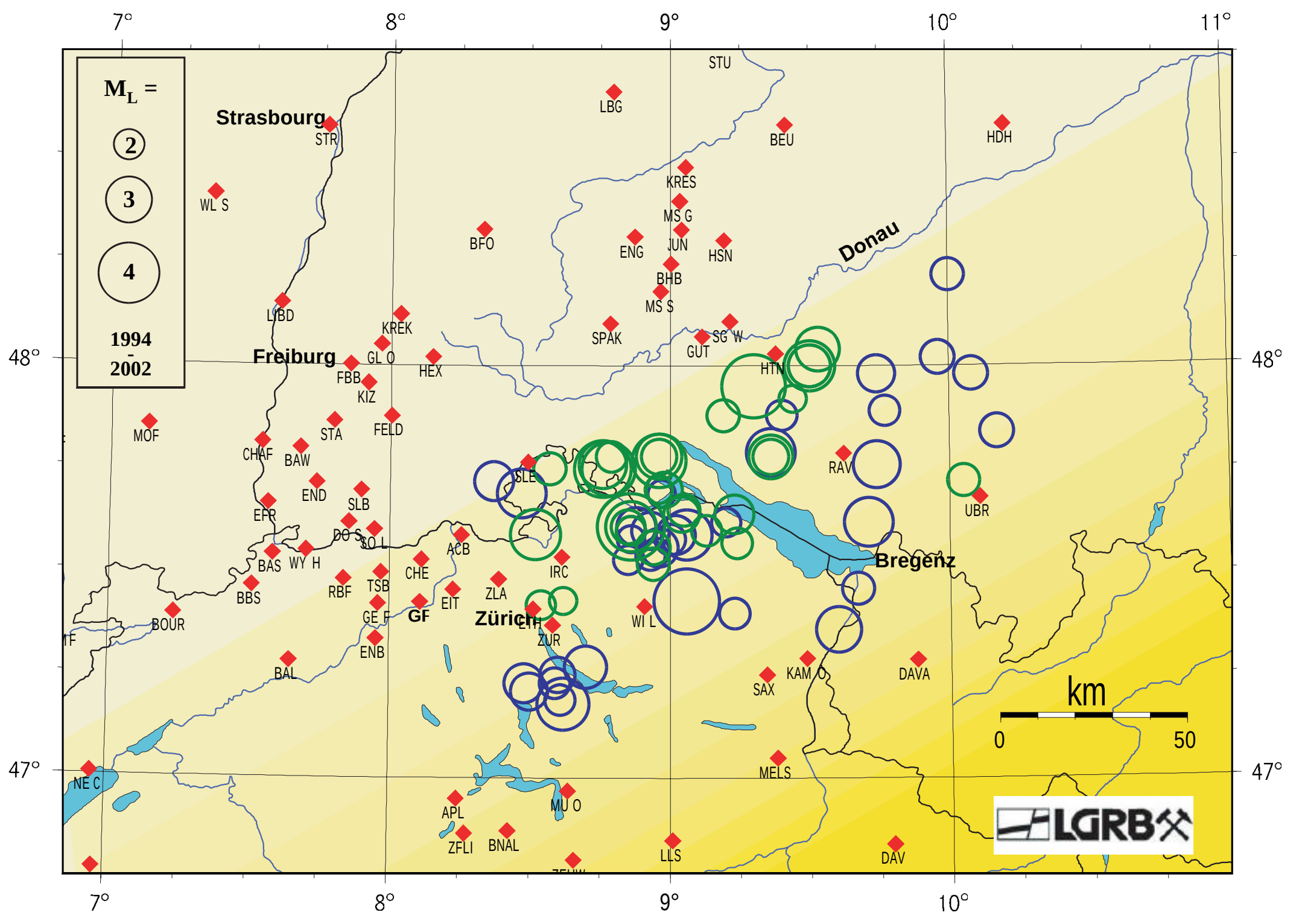


Fig. 1: Map of northern Alpine foreland showing seismic stations (red triangles) and relocated earthquakes (green circles: upper crustal foci; blue circles: lower crustal foci). Gradation in the background color indicates the deepening of the Moho toward the Alps. Some of the stations shown were closed or opened during the period of investigation.

Seismological Data

We have relocated earthquakes in the Swiss-German-Austrian border region (extending from Lake Zürich across Lake Constance to the Iller river), using seismograms recorded by the seismic network of the State of Baden-Württemberg and by other German, Swiss, Austrian, and French stations (Fig. 1). Hypocenters can be determined with a relative accuracy of up to 3 km by including travel times of seismic waves reflected at the Moho (Fig. 2) and an approximate Moho topography based on seismic profiles (Fig. 3). The absolute precision of hypocenter location is limited by the accuracy of the one-dimensional seismic velocity model (Fig. 5).

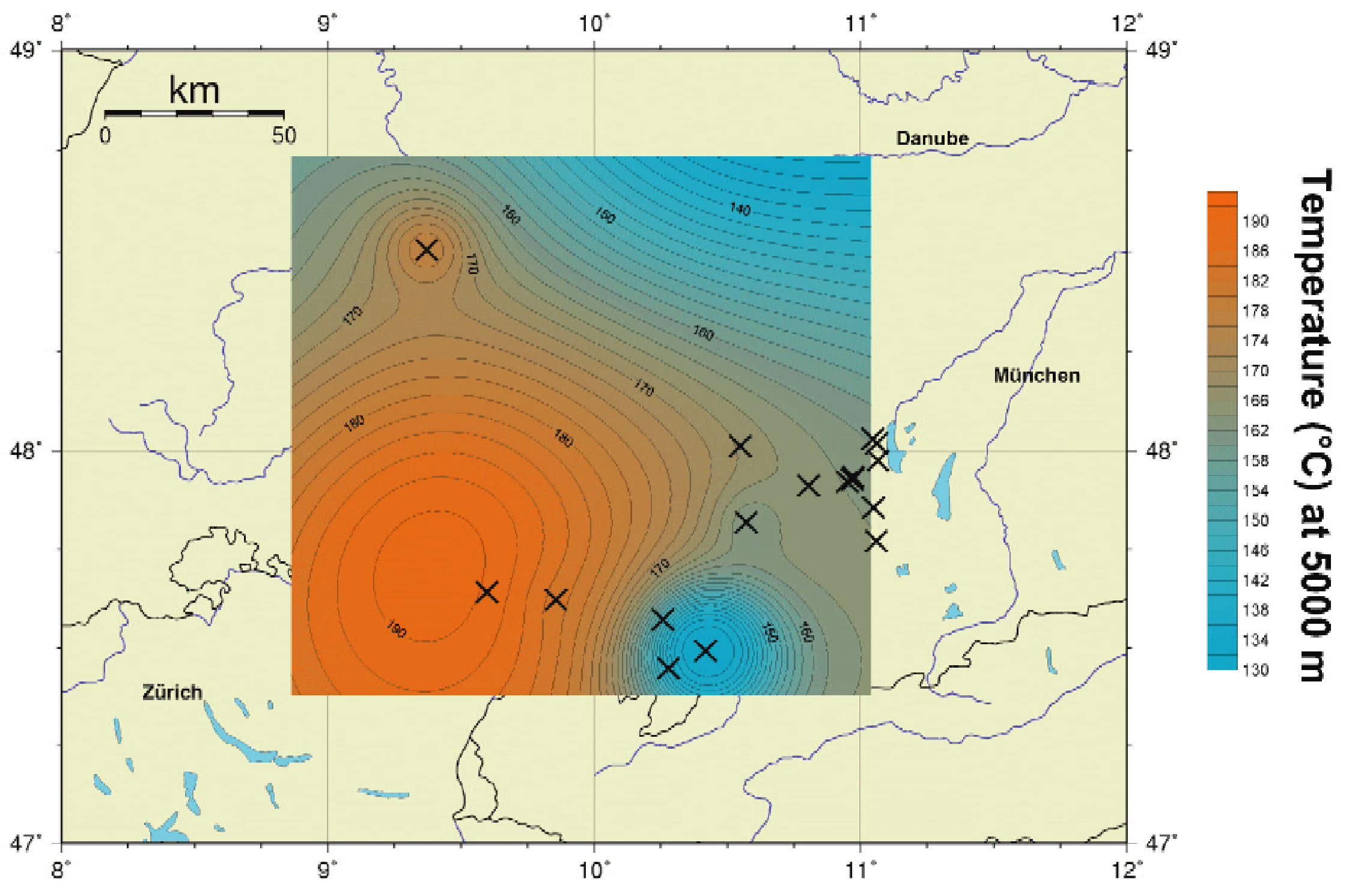
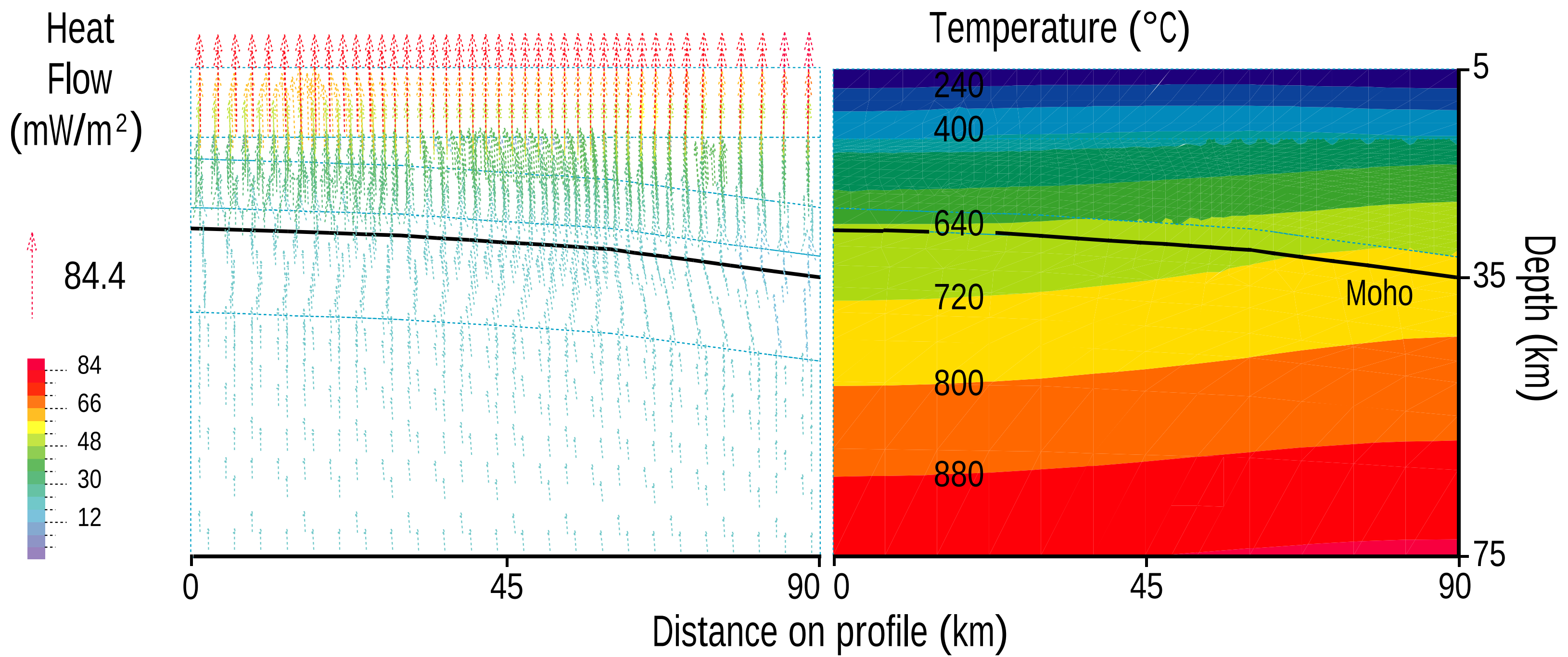


Fig. 6: Map of temperature isolines interpolated from distributed temperature measurements in boreholes in the Molasse Basin and the underlying basement at 5 km depth (gridded values courtesy of W. Rühaak, GGA Hannover). Temperature in the seismically active region (southwestern section of map) averages 180 +/- 10 °C. Crosses indicate locations of deep drill holes with temperature measurements.



Suggestions for Research

- Seismology: Improved seismic velocity structure and earthquake locations
- Stress field models: 3-D flexure including variable orogenic loading/unloading
- Geothermics: Effects of sediment blanketing, uplift, erosion, fluid flow
- Hegau xenoliths: Geochemical analysis, age determination, physical properties
- Rock mechanics: Experiments under variable fluid pressure and composition
- Rheology: Improved models, flow instabilities, reaction-enhanced embrittlement
- Hydrochemistry: Carbon and helium isotope analysis of spring waters
- Electromagnetic induction: Resistivity structure, to possibly resolve free fluids
- Neotectonics: Active faults? Seismites in sediment cores from Lake Constance?

References

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Strehlau, J. & C. Williams (1998): *Mitteilungen der Deutschen Geophysikalischen Gesellschaft*, Special Issue **II**/1998 "Heat Transport in the Crust", pp. 106-111.

Introduction

The lower crust is usually thought to deform by ductile flow under high temperatures. However, under the Molasse Basin in the northern Alpine foreland (Fig. 1) earthquakes occur not only in the upper crust, but also in the lower crust (e.g., Deichmann & Rybach, 1989). Since laboratory friction experiments under hydrothermal conditions (at constant fluid pressure) show aseismic stable sliding, it is enigmatic why the deep crust can become seismogenic. With the broad variety of observations (seismic profiles, xenoliths, geothermal data from oil exploration drillholes, etc.) available from the Molasse Basin, this region may be a key area for developing and testing new concepts of the relationship between earthquakes, stresses, temperatures, deformation, and metamorphism. The purpose of the present contribution is to synthesize seismological, petrological, and geothermal results into a self-consistent starting model.

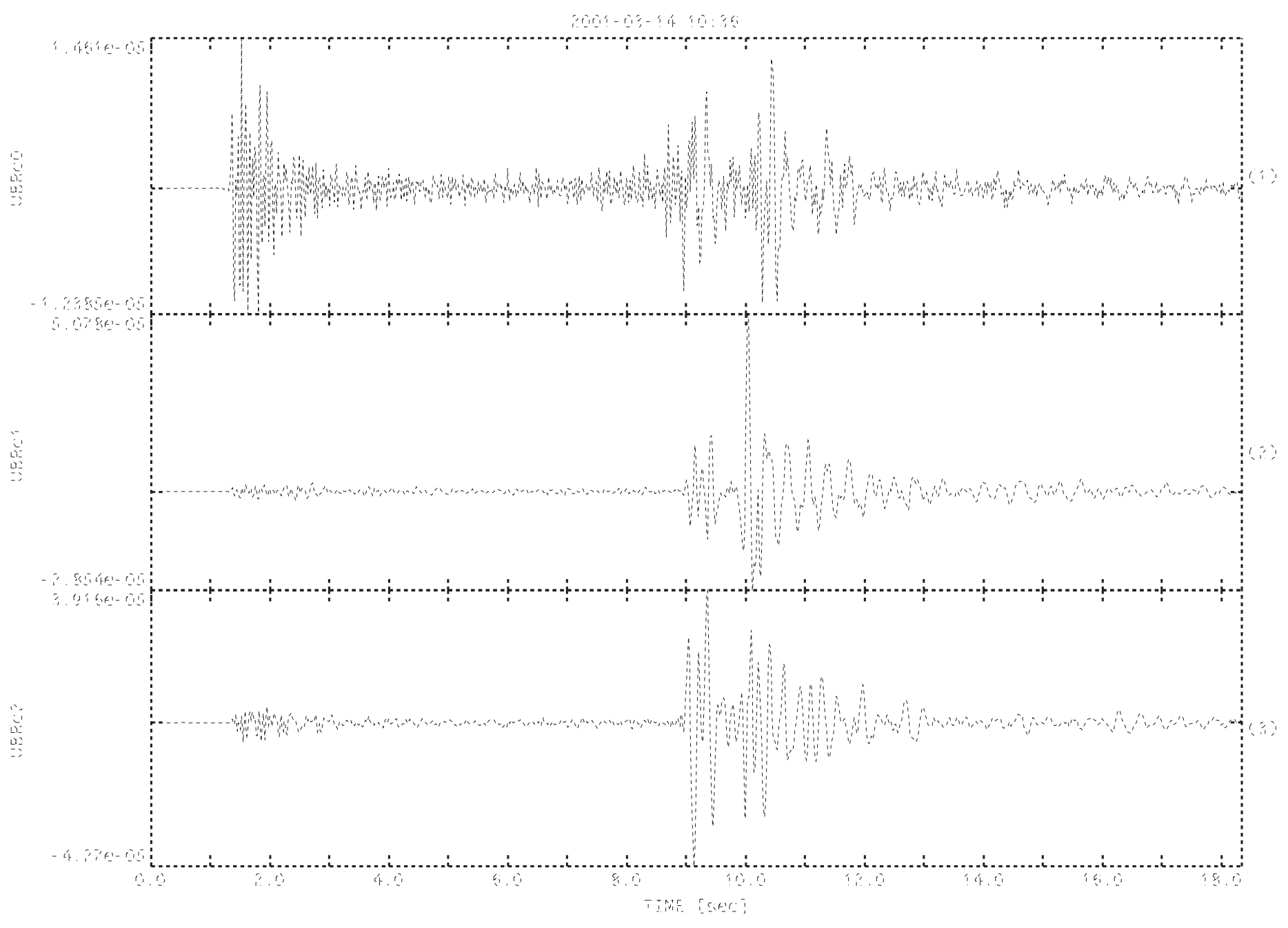
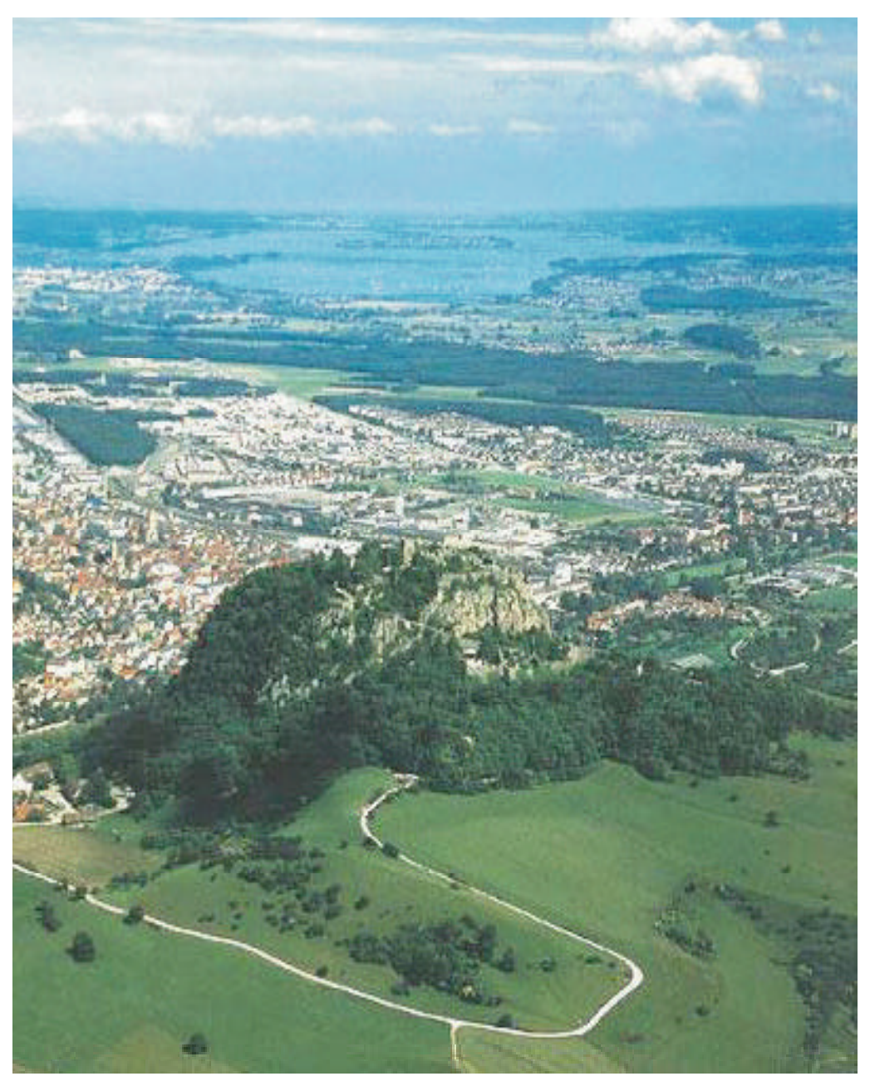


Fig. 2: Example of seismograms from the deep crustal earthquake at Feldkirch (southwesternmost epicenter in Fig. 1). Top panel: vertical component; middle and lower panels: horizontal components. Strong phases arriving about 0.5 sec after the P-wave and about 1 sec after the S-wave are interpreted as Moho reflections (PmP, SmS; wave trains probably also contain converted phases, e.g. PmS and SmP).

Fig. 4: View toward the SE showing the Miocene intrusive phonolite of Hohentwiel volcano (Hegau volcanic province; location see top margin of Fig. 3), across city of Singen toward westernmost embayments of Lake Constance (Zeller See, Untersee).



Thermal Modeling

Steady-state temperature estimates for the deep crust have been calculated using the commercial finite element software "ADINA System" (900 nodes version). Since geotherms depend on model parameters, temperature-dependent thermal conductivity and heat production are reasonably well constrained by the xenolith observations.

The results for a model structure with a dipping crust (cf. Fig. 3) show geotherms cutting across the Moho rather than following it (Fig. 7). This effect is caused by the lateral increase of total heat production due to greater crustal thickness. Moho temperature thus ranges from 640-740 °C.

From a systematic variation of the thermal parameters, temperatures at the seismic-aseismic transition for the deep crustal earthquakes are estimated to range from 570-800 °C (Fig. 8). Comparison with a metamorphic facies diagram indicates that the deep crustal earthquakes may occur at the amphibolite-granulite transition.

Seismogenic faulting may therefore be associated with active metamorphism, perhaps involving episodic hydration and/or dehydration reactions. However, many uncertainties and open questions remain. These could be addressed by a research effort integrating several different approaches.

Fig. 7: Steady-state thermal conduction model for a 90 km-long by 70 km-deep cross-section parallel to the profile shown in Fig. 3; top edge at 5 km depth, with laterally varying temperature values according to results shown in Fig. 6. Right panel: Geotherms; left panel: heat flow, arrows indicate direction of heat flow at individual finite elements. Constant mantle heat flow of 20 mW/m² assumed at lower edge. Thin blue lines: Model structure according to Fig. 5.

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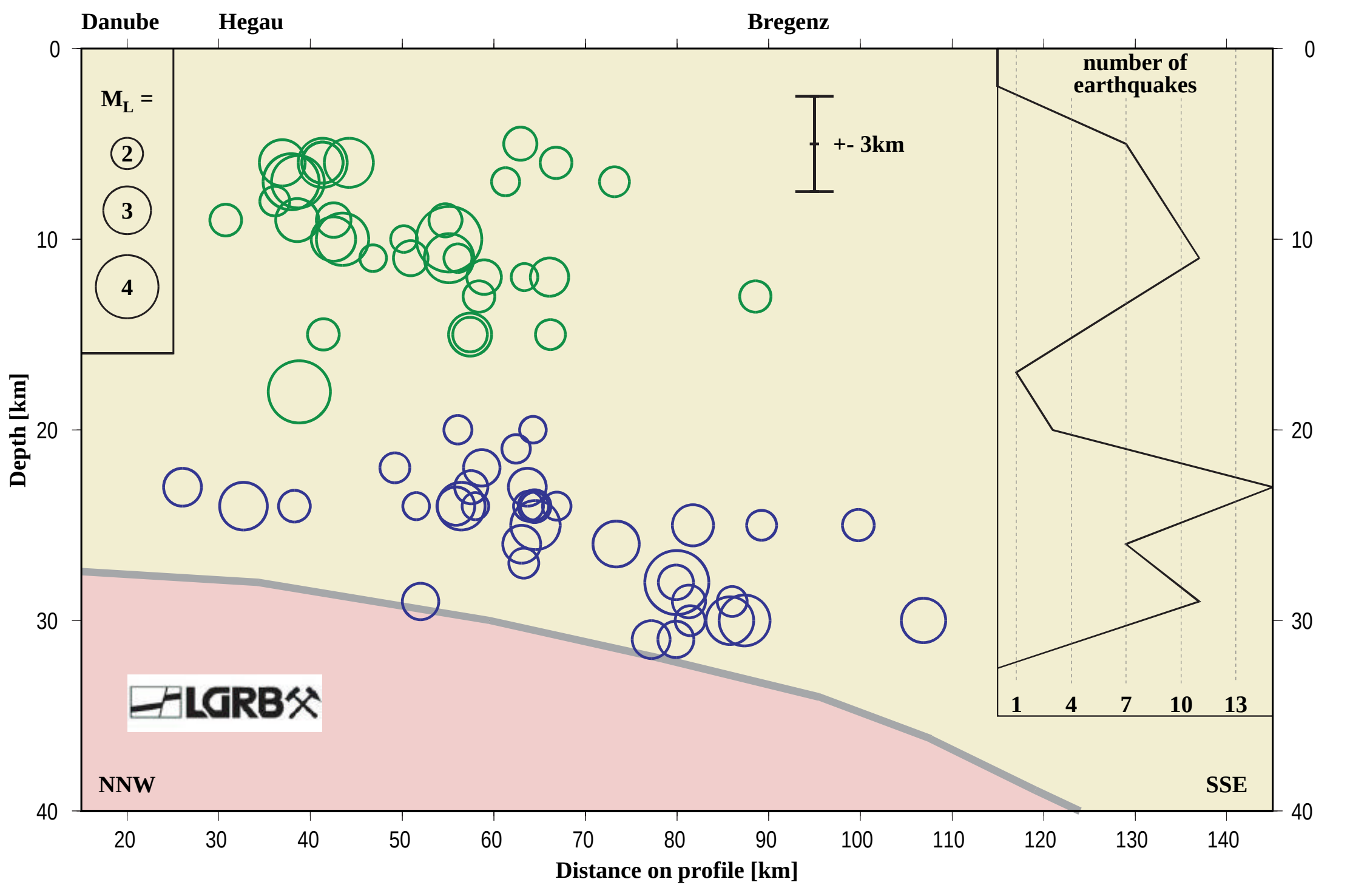


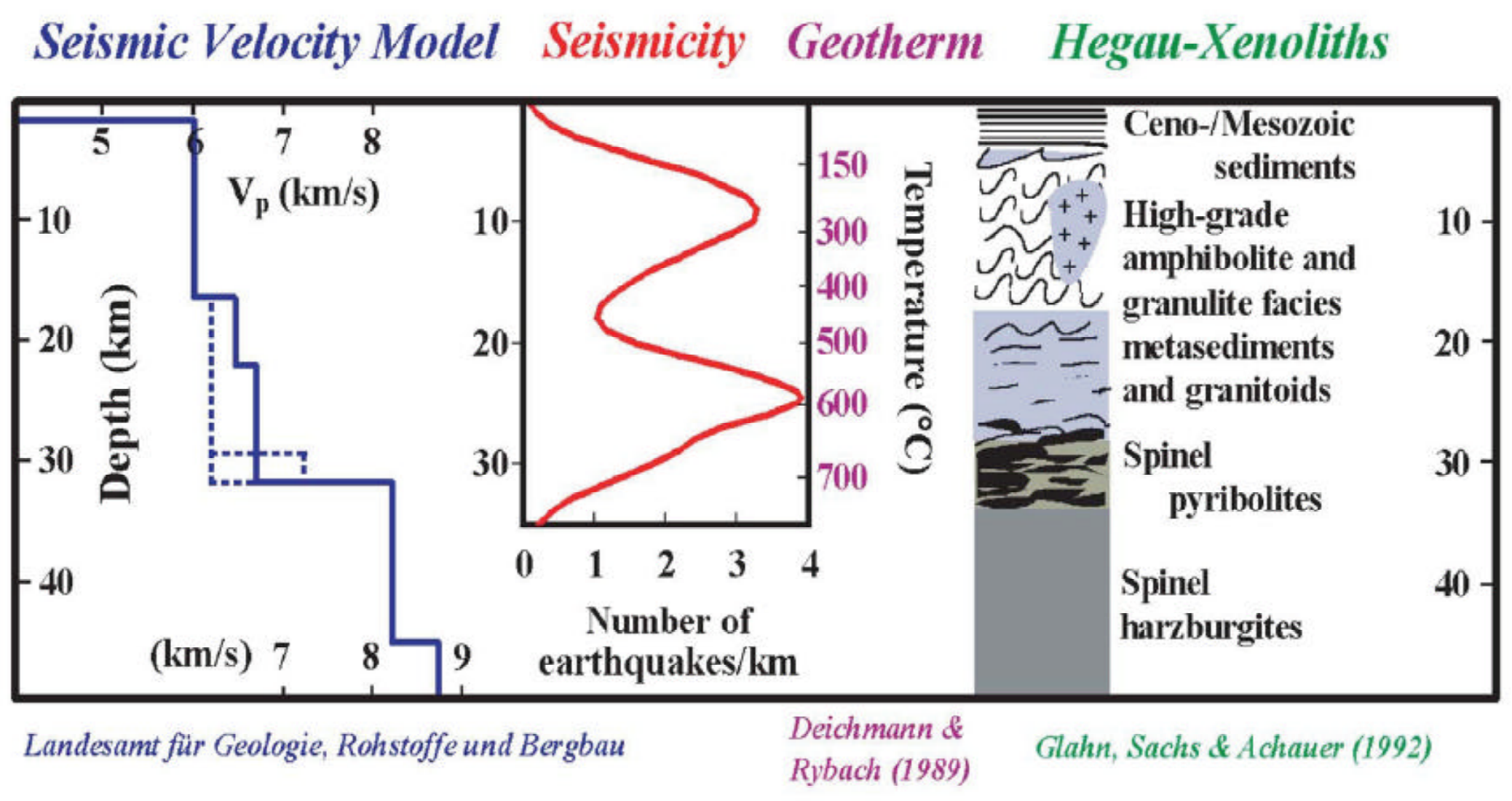
Fig. 3: Cross-section (azimuth S30°E, roughly parallel to the strike of Lake Constance, cf. Fig. 1), showing distribution of hypocenters and the number of earthquakes with depth (inset; 3 km bins). Pink: upper mantle; grey line: Moho.

Depth Distribution of Earthquakes

Except at the northwestern margin of the Molasse Basin, two distinct seismogenic depth intervals are resolved: one in the upper crust to 16 km, the other in the lower crust from 20 km to the Moho, separated by an apparently "aseismic" middle crust from 16-20 km (Fig. 3). The top edge of the lower zone tends to follow the Moho as it deepens toward the Alps. No deep crustal earthquakes have been located under the Alps. No systematic variation of magnitude with depth has been found.

Interpretation

The depth distribution is correlated with the average seismic velocity model used in the location procedure, and with a lithological structure deduced from xenoliths sampled in the Hegau volcanic province (Figs. 4 and 5). The P-wave velocity of the deep Molasse crust is relatively low (6-6.7 km/s), except for the thin crust-mantle transition zone. The xenoliths are dominantly metapelitic and granitic gneisses, whereas only few have been found with a mafic spinel-pyroxene granulitic composition (pyribolites). Consequently, the low seismic velocities and the relative proportion of mafic and felsic xenoliths exclude mafic granulites as a major component of the lower crust. The mafic granulites have accordingly been assigned to the crust-mantle transition zone. The lower crustal seismicity can therefore not be explained by a strong, mafic lower crust.



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Deichmann & Rybach (1989)
Glahn, Sachs & Achauer (1992)

Fig. 5: Correlation between seismic velocity model (blue line, dashed: alternative model), smoothed seismicity-depth distribution (red curve, from Gaussian summation of individual uncertainty ranges), average temperature estimates at corresponding depths under the Swiss part of the Molasse basin east of Lake Zürich (purple values), and lithological model column derived from the Hegau xenoliths.

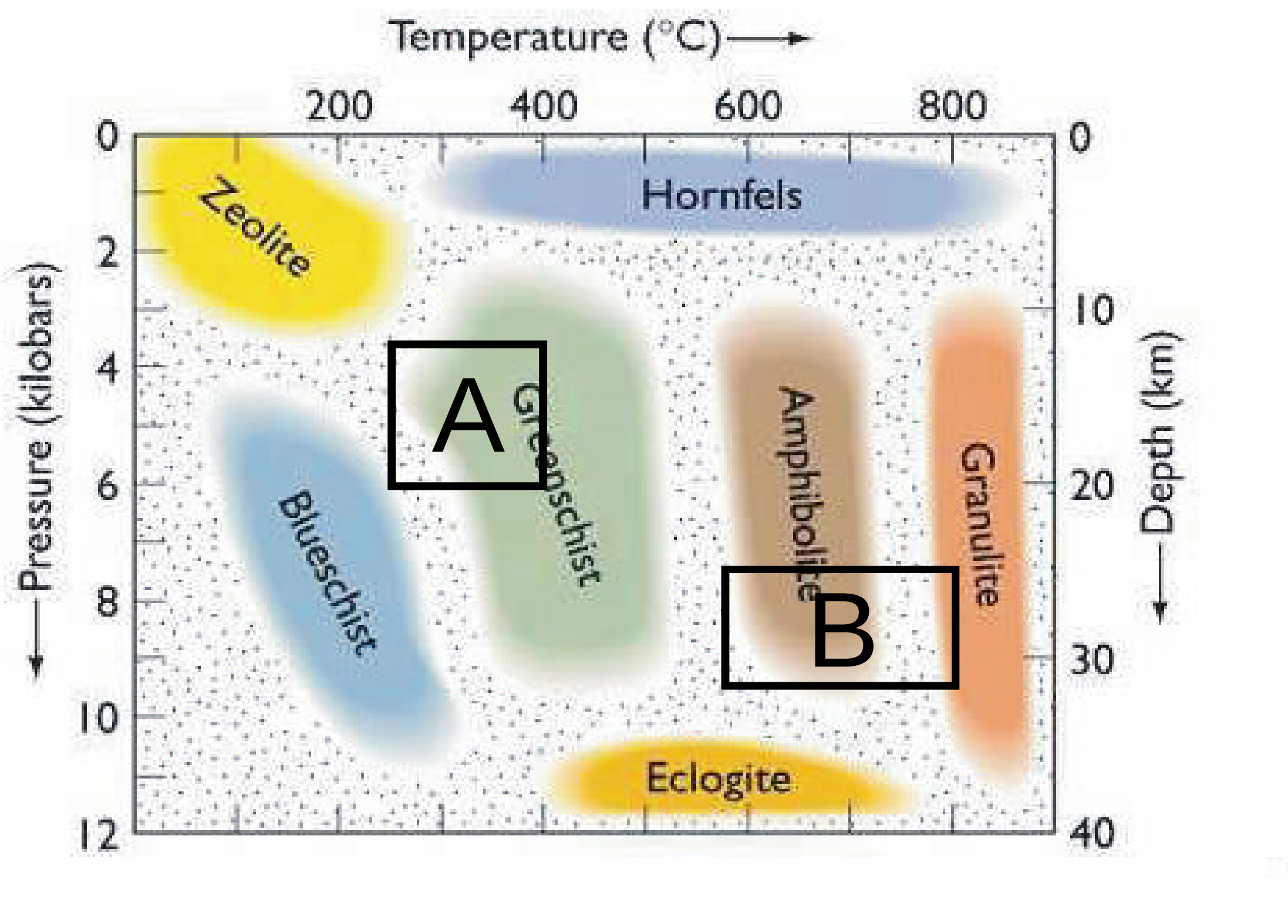

Fig. 8: Pressure-temperature-depth diagram showing outlines of metamorphic facies domains and estimates of conditions at the seismic-aseismic transition in two different regions. Box A: upper crustal earthquakes on the San Andreas fault system, California (Strehlau & Williams, 1998); box B: lower crustal earthquakes under the Molasse Basin (Deichmann & Rybach, 1989; this study).

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