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A stress measurement profile to mid-crustal depth in KTB scientific drilling project, southeastern Germany: scientific questions and technological challenges

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Although many estimates of crustal stress levels at seismogenic depth have been made on the basis of laboratory data and simple faulting theory, the *Kontinentales Tiefbohr* (KTB) deep drilling project offers the first opportunity to directly measure at mid-crustal depth the absolute magnitudes of crustal stresses, the uniformity of stress changes with depth, the influence of pore pressure on stress magnitude and the magnitude and orientation of tectonic stresses in the vicinity of the brittle–ductile transition. The planned 10–12 km depth of the KTB *Hauptbohrung* (main borehole) will penetrate those depths where the shear stresses in the crust are highest and where the greatest discrepancy will exist between observations and predictions if either 'Byerlee's law' is not applicable to the mid-crust or near-lithostatic pore pressure exists which substantially weakens the crust.

Consistent with measurements in the upper 3 km at a number of sites around the world, stress magnitudes measured to 3 km depth in the 4 km deep KTB *Vorbohrung* (pilot hole) were found to be in agreement with Byerlee's law. However, there are a number of problems with simply extrapolating such data to mid-crustal depth. First there is now a substantial body of information that indicates that plate boundaries move at shear stress levels appreciably lower than those predicted by Byerlee's law. As we do not yet understand the origin of this weakness, it is not clear whether the processes responsible for it might also apply to plate interiors. Second, in a number of intraplate continental areas, it is now clear that the state of stress is closely related to plate-driving processes. However, the magnitude of plate-driving forces is considerably less than that required to cause intraplate deformation, especially in regions of reverse and strike–slip faulting like eastern North America. Third, it is essentially impossible to predict the relationship between pore pressure and stress magnitude at the depths where the brittle–ductile transition is approached. The onset of creep and ductile deformation would seem to be associated with the closure and healing of microcracks resulting in pore fluids trapped in isolated cracks and pores. This would cause a breakdown of the effective stress principle and a marked increase of crustal strength (making the discrepancy between the magnitude of plate-driving forces and crustal strength even more severe). However, geologic evidence from veining and the nature of earthquake focal plane mechanisms from some earthquake swarms, indicates that in some places, at some times, near lithostatic

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fluid pressures exist at mid-crustal depth. For these reasons we believe that continuous determination of stress magnitudes and orientation to mid-crustal depth are key experiments of the KTB project and of broad-scale scientific interest.

Techniques for measurement of *in situ* stress magnitudes standardly used at shallower depth are difficult to impossible to apply at mid-crustal depth. For this reason, we have developed an integrated stress measurement strategy that involves (1) a modification of the conventional hydraulic fracturing technique at relatively shallow (*ca.* 4–6 km) depth utilizing aluminium packers in small-diameter pilot holes drilled periodically at the bottom of the *Hauptbohrung*, (2) hydraulic fracturing through cemented casing that will potentially make measurement of the magnitude of the least principal stress possible to the total depth of the hole, and (3) estimating the magnitude of the greatest horizontal principal stress from the detailed analysis of compressional and extensional wellbore failures. This requires utilization of knowledge of the magnitude of the least principal stress (made available from the hydraulic fracturing tests), rock strength and pore pressure.

Discussion

P. England (*Oxford University, U.K.*). First it seems to me that Professor Zoback's difficulty with Byerlee's law comes about through estimates of stress which he makes in the upper mantle and those estimates depend more strongly on temperature at the Moho than anything else, which I think he must admit is rather indeterminate. So possibly the problem really resides in the estimates of stress from Byerlee's law in the middle crust. When he said that pore pressure in the middle crust is essentially equal to static pressure this would imply a great variety of focal mechanisms. Does that implication still hold up if there is a kinematic constraint on the deformation, if it is imagined that the whole of the crust is being driven by distributed tractions applied to its base by a stronger substrate? Would he not then get consistent sets of focal mechanisms and that would then let him postulate high pore pressures in the crust?

M. D. Zoback. I agree that the temperature in the upper mantle is the predominant parameter controlling mantle strength, and thus how much plate-driving force the mantle is 'carrying'. However, the problem I alluded to, the discrepancy between the overall strength of the lithosphere and the amount of force available to cause lithospheric deformation, is primarily the result of applying Byerlee's law with hydrostatic pore pressure through the brittle part of the upper crust in compressional environments. Thrust faulting to a mid-crustal depth of about 15 km using Byerlee's law with hydrostatic pore pressure requires a cumulative force of about 7×10^{12} N m^{-1} which is about 50% greater than the forces generally thought to be available to deform the lithosphere. This is independent of temperature as it involves no force being carried in the ductile lower crust or upper mantle. So indeed, the question is the validity of the assumption that Byerlee's law is applicable with hydrostatic pore pressures. The way out of this problem is to make the brittle crust much weaker. An extremely low coefficient of friction (incompatible with Byerlee's law) or a very high (near lithostatic) pore pressure are two ways to do this. The question of whether the uniformity of the P- and T-axes in intraplate areas is the result only of kinematic constraints is an interesting one. For this to be true it implies that earthquake focal-plane mechanisms tell us only about strain (and nothing about

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stress). This can be true only if the frictional strength of the faults is close to zero. So, basically, we reach the same conclusion no matter how we interpret the deep focal-plane mechanisms. If they are stress indicators the frictional strength of the crust appears to be too high; if they are only strain indicators the frictional strength of the crust must be close to zero.

N. Kusznir (*Liverpool University, U.K.*). The strain rates shown are exceedingly rapid, 10^{-15} is 100% stretching in 30 Ma. It is a respectable rate for forming an extensional basin. By the time 10^{-11} is reached I don't think any process on the Earth goes that fast. Obviously if one reduces the strain rates, one reduces the force quite substantially.

M. D. Zoback. The examples of strength envelopes I was using were made for plate boundaries and not for intraplate areas and thus the strain rates were indeed too high for an intraplate region. However, as in my response to the question by Dr England, the assumed strain rates (like temperature) only affect the strength of the ductile lower crust and upper mantle and the problem of lithospheric strength against lithospheric force comes from what is happening in the brittle part of the upper crust, from the applicability of Byerlee's law and from hydrostatic pore pressure.

M. H. P. Bott (*Durham University, U.K.*). The heat flow Professor Zoback presented is about the continental-shield heat flow and the gross strain rate is certainly very small in such areas. The same of course applies to oceanic lithosphere. Is this the reason why these regions are not deforming and why they have strength and the movements are concentrated in the hot regions? Further would this suggest in field areas that the upper part may be in frictional equilibrium, while in the lower part the stresses are much less?

M. D. Zoback. I think this suggestion is quite likely. In fact, other calculations I have done suggest that it may be that only in areas of very low heat flow (like shields and old ocean basins) that the upper mantle can carry much plate-driving force (and thus the crust does not have to!). So indeed, perhaps this is why deformation rates are so low in such areas.

T. Harper (*BP Research Centre, Sunbury, U.K.*). I think we know enough about the evolution of faults to appreciate, from fairly recent studies over the past five or ten years, that the state of stress evolves around any particular fault which has a finite geometry and a finite extent and, as fluid flow is associated with it, it is a quite complicated evolution. It seems to me that if Professor Zoback's measurements are consistent with a long structure with one block sliding over the other, either he is making his measurements remote from the sliding fracture, or the idea of an evolving stress distribution round a finite fault somehow does not apply in his case. He had a scatter of something like 60° over quite a large amount of the data. I think that we need to try to define what is a significant variation. Can he attach a number to this term?

M. D. Zoback. The interesting thing about stress measurements near major active faults is both their uniformity and variability. For example, near the San Andreas fault in central California, the direction of maximum horizontal stress from scores of

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wellbore breakouts and earthquake focal-plane mechanisms adjacent to the fault, indicate a remarkably uniform direction of maximum horizontal stress oriented nearly perpendicular to the strike of the fault. At the same time, detailed studies of stress orientation to 3.5 km depth in the Cajon Pass research borehole adjacent to the San Andreas fault in southern California show a well-established mean stress orientation (approximately perpendicular to the local strike of the San Andreas fault) with a standard deviation of 19°, but numerous small-scale fluctuations due to motion on small faults penetrated by the borehole. The only places where large scatters of 60° exist (such as those Dr Harper refers to), are associated with these extremely localized stress perturbations. The average stress field is fairly uniform.