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IT has been suggested[1–6] that in many cases the average strength of the continental crust is quite low (tens of megapascals), so that the crust has little effect on the large-scale deformation of the lithosphere. But laboratory friction studies[7,8], combined with simple faulting theory[9,10] (as well as extrapolation of *in situ* stress measurements from the upper 3 km of the crust[11]), imply that if pore pressure is approximately hydrostatic at mid-crustal depth, crustal strength is appreciable (hundreds of megapascals) and would markedly constrain the nature of lithospheric deformation[12–15]. Here we report estimates of the magnitude of *in situ* stresses to 6 km depth in the KTB borehole in southern Germany. Our results indicate a high-strength upper crust, in which the state of stress is in equilibrium with its frictional strength. We suggest that plate-driving forces in the continental lithosphere in this part of western Europe are transmitted principally through the upper crust, and that this may also be the case in other continental areas of moderate to elevated heat flow.

The KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) drillsite is located in an area of occasional minor seismicity where highly deformed Palaeozoic metamorphic rocks have been intruded by Variscan (late Palaeozoic) granites. In the first phase of the drilling project (completed in 1989), a pilot hole was continuously cored to a depth of 4 km. It encountered a highly folded and steeply dipping sequence of foliated gneisses and intercalated massive amphibolites. Stress measurements in the pilot hole[16,17] show a NNW-oriented direction of maximum horizontal principal stress and strike-slip to normal faulting stress magnitudes. These quantities are similar in orientation and relative magnitude to those found in much of central Europe[18,19]. The second phase of the project involves drilling a much larger diameter borehole to a total depth of 10 km. Below 3.2 km in the main borehole, nearly all the rock is relatively massive amphibolite from apparently the same rock units encountered at shallow depth.

An integrated stress-measurement strategy was developed to determine *in situ* stress magnitudes to 10 km depth in the main borehole. An important part of this strategy was to propagate a hydraulic fracture away from a ~20-m-long section of open hole that was drilled after steel casing was cemented into the hole at 6 km. From such a 'hydrofrac' test one can determine the magnitude of the least principal stress from the so-called 'shut-in' pressure[20] and low-flow-rate pumping pressure[21]. We assume that the least principle stress corresponds to S_{hmin}, the least horizontal principal stress, as one principal stress generally appears to be vertical in the upper crust (corresponding to the lithostat, S_V[22]) and in the KTB boreholes there are ubiquitous near-vertical drilling-induced tensile fractures (described below) which indicate a near-vertical principal stress[23]. One cannot obtain confident estimates of the maximum horizontal principal stress, S_{Hmax}, from the type of hydrofrac test conducted at 6 km because fracture initiation is likely to be affected by the irregular shape of the borehole wall caused by stress-induced wellbore breakouts (described below) and/or pre-existing fractures. The pressure record from which the magnitude of S_{hmin} was determined is shown in Fig. 1*a*. Both the shut-in pressure and low-flow-rate pumping pressure indicate that the least principal stress has a magnitude of 114 ± 5 MPa.

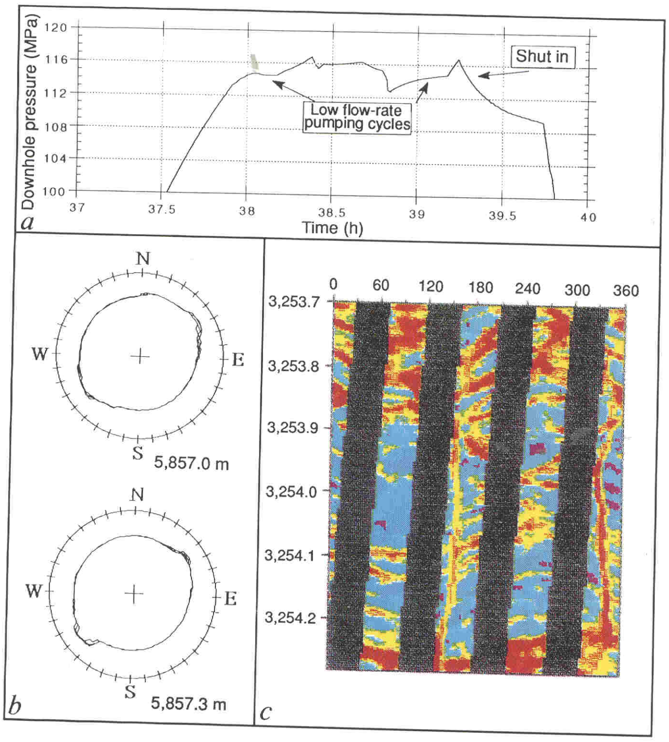

FIG. 1 *a*, Downhole pressure recorded during the hydraulic fracturing test. *b*, Cross-sectional shape of the borehole in an interval of stress-induced wellbore breakouts. Note that the breakouts occur ~180° apart (as expected from the concentration of elastic stress around the wellbore). The azimuth of elongation corresponds to the direction of least horizontal compression. *c*, A fine-scale electrical conductivity image of the inside of the borehole wall. Vertical axis is depth in metres, horizontal axis is azimuth around the wellbore with respect to north, colour indicates fine-scale electrical conductivity (red is high conductivity, yellow is intermediate, purple is low) and black bands indicate sections of the borehole wall where no data was obtained. Near-vertical drilling-induced tensile fractures cut across foliation planes in the rock. As theoretically expected, the tensile fractures occur 180° apart, in the direction of maximum horizontal compression.

To estimate the magnitude of S_{Hmax}, the integrated stress-measurement strategy uses the hydrofrac-determined value of S_{hmin} coupled with analysis of compressive and tensile failures around the wellbore. These failures result from the stress concentration associated with drilling an initially circular hole into a pre-stressed medium[24]. Detailed inspection of the KTB pilot and main boreholes with ultrasonic and electrical imaging devices indicates that there are many depth intervals where the rock surrounding the borehole is simultaneously failing in compression and tension as it is being drilled. That is, stress-induced compressive failures (or wellbore breakouts) (Fig. 1*b*) are observed at the azimuth of S_{hmin} (where the stress concentration is most compressive) and drilling-induced tensile fractures (Fig. 1*c*) are observed at the azimuth of S_{Hmax} (90° from the breakouts) where the stress concentration is least compressive.

To estimate S_{Hmax} from the occurrence of wellbore breakouts, we used information regarding (1) the least principal stress determined from hydraulic fracturing, (2) rock strength determined from laboratory measurements on cores, and (3) the circumferential angle over which the wellbore failed, as determined from detailed analysis of borehole televiewer data. The theoretical basis for this technique and its detailed application to the KTB pilot hole is described elsewhere[25,26]. Uncertainties in the computed values of S_{Hmax} (Fig. 2) result from the combined uncertainties in rock strength and variations of the shape of the breakouts around the wellbore.

Drilling-induced tensile failures at the borehole wall arise from the combined effects of the stress concentration around the borehole, cooling-induced tensional stresses (resulting from circulation of relatively cold drilling mud into the hole) and the excess pressure in the borehole during drilling[27]. The near-vertical tensile fractures in the KTB pilot and main boreholes are clearly drilling-induced. They are not present in the cores, but are observed (as theoretically expected) at the azimuth of S_{Hmax} and cut across pre-existing planes of weakness such as foliation planes. Determination of S_{Hmax} from the drilling-induced tensile fractures involved several steps. First, we assumed that the rock has no tensile strength because these fractures could initiate at a pre-existing flaw around the wellbore. Second, because it was not known how much cooling was necessary to induce the observed thermal fractures, we calculated maximum and minimum values of S_{Hmax} corresponding to the full range of temperatures and excess borehole pressures during drilling at which the fracture might have initiated. The upper bound for S_{Hmax} is calculated by assuming that the fractures occurred with no borehole cooling (that is, simply as a result of the tectonic stress concentration) and no excess fluid pressure during drilling, whereas the lower bound is calculated by assuming that the fractures occurred after the maximum amount of borehole cooling occurred (Fig. 2). (More details of the analysis of drilling-induced fractures are contained in a preprint by R.A., M.D.Z. and K.F., see Supplementary Information.)

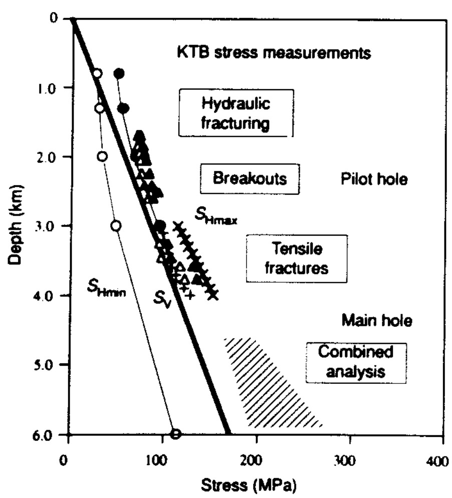

FIG. 2 S_{hmin} and S_{Hmax} values in the KTB pilot hole and main borehole. The values determined from the hydraulic fracturing measurements are indicated by ○ (S_{hmin}) and ● (S_{Hmax}). The upper- (▲) and lower-bound (△) estimates of the magnitude of S_{Hmax} determined from wellbore breakouts (as well as the hydrofrac-determined S_{hmin} values) are also shown. The upper and lower bound S_{Hmax} values determined from analysis of drilling-induced tensile fractures are indicated by + and ×, respectively. The combined analysis (shown by the hatched area), refers to the upper and lower bound estimates of S_{Hmax} between 4.5 and 6 km depth in the main borehole which are consistent with the occurrence of both tensile fractures and breakouts. The vertical stress is based on the average measured density of 2.8 g cm^{-3}.

Because the magnitude of S_{hmin} and S_{Hmax} are known to 3 km depths from convential hydraulic fracturing stress measurements in the KTB pilot hole (ref. 16; also available as Supplementary Information), we can compare the values of S_{Hmax} obtained by analysis of the breakouts and tensile fractures with that determined from hydraulic fracturing, and thus effectively calibrate the integrated stress-measurement strategy. As shown in Fig. 2, the S_{Hmax} values determined from the breakout analysis compare extremely well with the direct hydrofrac-determined values in the pilot hole[28]. A similarly good match between breakout-determined and hydrofrac-determined S_{Hmax} values was found in the 3.5-km-deep Cajon Pass scientific research borehole[25]. The data required to estimate S_{Hmax} from the tensile fractures in the KTB pilot hole were available only at depths between 3 and 4 km. The values of S_{Hmax} determined from the tensile fractures in that interval compare extremely well with the values of S_{Hmax} estimated both from the breakout analysis at the same depths and from extrapolation of the hydrofrac-determined S_{Hmax} values.

In the interval between 4 and 6 km, we used an analysis of both the drilling-induced tensile fractures and breakouts to obtain the range of values for S_{Hmax} shown in Fig. 2. Although the uncertainty in S_{Hmax} at great depth is appreciable (reflecting the cumulative uncertainties in the various parameters noted above), a strike-slip faulting stress regime is clearly indicated (the vertical stress is the intermediate principal stress) and the maximum differential stress ($S_{Hmax}-S_{hmin}$) is substantial (>100 MPa).

The maximum differential stresses determined in the KTB pilot and main boreholes are summarized in Fig. 3*a* and compared to theoretical estimates of the maximum principal stress difference in the crust. The strength profile in Fig. 3*a* is for the case of strike-slip faulting in the upper crust (appropriate for the KTB region[29] and consistent with the *in situ* stress measurements), a coefficient of friction (μ) of 0.7 (ref. 7) and hydrostatic pore pressure (which is consistent with pore pressure measurement in the KTB borehole to 6 km depth). To derive the linear increase of frictional strength with depth in the upper crust, we calculated the value of S_{Hmax} required to cause frictional sliding on pre-existing fault planes for the measured values of S_{hmin}. Based on these assumptions, the maximum differential stress reaches values of ~300–400 MPa in the mid-crust. As shown in Fig. 3*a*, the differential stress values determined to 6 km in the KTB main borehole are consistent with the strength of the upper crust based on laboratory measurements and simple frictional faulting theory.

To consider the strength of the upper crust in the context of how the lithosphere transmits plate-driving forces, it is necessary to estimate the ductile creep strength of the lower cust and upper mantle. To do this we must estimate temperature at depth, assume an appropriate strain rate and use appropriate rheological values determined from laboratory experiments. Temperatures in the lower crust and upper mantle are based on a conductive thermal model based on the observed geotherm and relatively high heat flow (~74 mW m^{-2}) observed at the KTB

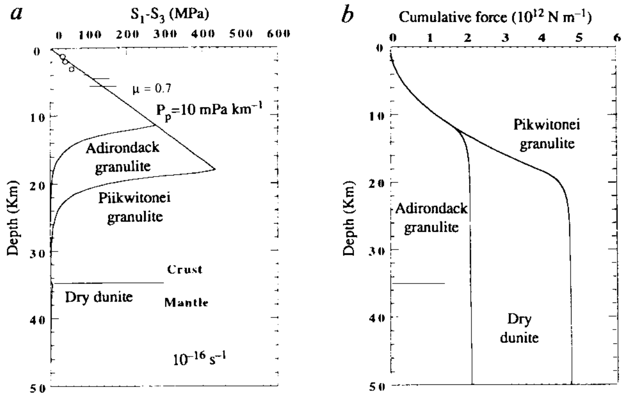

FIG. 3 *a*, Theoretical maximum differential stress ($S_1 - S_3$) profiles for conditions similar to those in the region of the KTB drillsite. Data points shown as ○ indicate the difference between S_{Hmax} and S_{hmin} as determined from hydraulic fracturing data to 3 km depth in the pilot hole. The data points shown as horizontal lines indicate a generalization of the values shown in Fig. 2 from the breakout and tensile fracture analysis. A strike-slip faulting stress regime with hydrostatic pore pressure and a coefficient of friction (μ) of 0.7 was used to calculate the theoretical strength in the upper crust (see text). *b*, Cumulative crustal force corresponding to the strength profiles shown in *a*).

site and in this part of central Europe. The values of thermal conductivity, radioactive heat production and the rate at which heat production decays are assumed to be typical values for continental crust[30,31]. We use the creep properties of Adirondack and Pikwitonei granulites as indicative of lower crustal rocks with very low and very high ductile strengths, respectively, at equivalent temperatures and strain rates[32]. Although the depth of the brittle–ductile transition implied by the lower-strength Adirondack granulite is reasonably consistent with the maximum depth (~12 km) of earthquakes in the region, it is unwise to place too much significance on this correlation as mechanisms other than the onset of crystal plasticity may play an important role in determining the depth of the brittle–ductile transition[33]. To obtain a maximum value of the ductile strength of the lower crust and upper mantle, we assume an average strain rate of 10^{-16} s^{-1}, which is a reasonable upper limit for plate interiors (at higher strain rates, plates would deform too much for plate reconstruction to be possible) and that the strength of the upper mantle corresponds to that of 'dry' dunite[32]. Note that despite these assumptions, the upper mantle deforms at extremely low differential stress levels because of its high temperatures.

The cumulative force required to cause lithospheric deformation (Fig. 3*b*) is equivalent to the area under the strength curves shown in Fig. 3*a* (ref. 3). Note that it takes a cumulative force of 2-5 × 10^{12} N m^{-1} to cause steady-state deformation of the lithosphere and that cumulative lithospheric strength is largely due to that of the upper, brittle crust.

The primary source of tectonic stress in western Europe appears to be related to the ridge-push force[18,34] resulting from the cooling and thickening of the lithosphere away from the Mid-Atlantic Ridge. The magnitude of ridge push averaged over the thickness of the lithosphere is ~2-5 × 10^{12} N m^{-1} (refs 35, 36). Because the available tectonic force is comparable in magnitude to the cumulative lithospheric strength, widespread seismicity in this part of western Europe appears to reflect steady-state failure equilibrium (at very low strain rate); force transmission through the lithosphere is largely in the upper 10–20 km of the crust, effectively in an upper-crustal stress guide. A similar process may also occur in the seismically active part of eastern North America as ridge-push appears to be the primary source of tectonic stress there[34,37] and heat flow is moderately high[31].

One can extend these arguments to geologically stable shield areas and relatively old ocean basins adjacent to western Europe and eastern Norh America, which are subjected to essentially the same lithospheric forces. As these regions are characterized by very low heat flow (~40 mW m^{-2}), upper-mantle strength is expected to be quite high (because of relatively low temperatures) and capable of supporting much of the total force acting on the lithosphere. Hence, significant lithospheric deformation would not be expected to occur because the cumulative strength of the lithosphere would be appreciably greater than the force available to cause deformation. □

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SUPPLEMENTARY INFORMATION. Requests should be addressed to Mary Sheehan at the London editorial office of *Nature*.

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