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published in
Geophys. Res. Letts.
1987

DOI (link to publisher)
10.1029/GL014i007p00741

document version
Publisher's PDF, also known as Version of record

GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 7, PAGES 741-744, JULY 1987

UNUSUALLY DEEP EARTHQUAKES IN EAST AFRICA: CONSTRAINTS ON THE THERMO-MECHANICAL STRUCTURE OF A CONTINENTAL RIFT SYSTEM

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Abstract. Shudofsky [1985] has established that earthquakes associated with the East African rift system have well-constrained focal depths as great as 25-30 km. Using published heat flow measurements as a guide to the local geotherm, we find through simple stress envelope calculations that the deepest earthquakes probably occur in the lower crust in a region where the lithosphere is strong. These results are at odds with the commonly held idea that seismicity in zones of continental extension is limited to the shallow upper crust because of elevated temperatures accompanying lithospheric thinning. Any model of the rifting process in East Africa must account for the fact that these regions exhibit considerable strength down to lower crustal levels.

Introduction

Numerous authors have used the depth-dependent rheological properties of probable crustal and upper-mantle materials to draw inferences concerning the operative geological and geophysical processes with depth in the earth [e.g., Vink et al., 1984; Morgan et al., 1986] . At the same time, well-constrained earthquake focal depths have been used to place constraints on the thermal and mechanical structure of the crust and upper mantle [e.g., Meissner and Strehlau, 1982; Chen and Molnar, 1983; Bergman and Solomon, 1984; Wiens and Stein, 1984]. Precise determinations of earthquake depths using teleseismic data are most commonly done using body wave modelling or inversion, which are robust to moderate uncertainties in earthquake source mechanism and time function [Stein and Wiens, 1986]. The good agreement between depth determinations derived by different investigators using different methods lends further support to their estimated attainable depth precision of 2 km. Allowing for further uncertainty due to lack of knowledge of the near-source structure, it is still reasonable to assume that earthquake depths may be determined to a precision of about 4 km.

The depth dependence of surface wave excitation has also been employed to estimate focal depths from teleseismic data [e.g., Tsai and Aki, 1970; Mendiguren, 1977; Romanowicz, 1982]. The primary restriction is the lateral heterogeneity of velocity structure within the earth. One way to improve the accuracy of depth determinations using surface waves is to employ a reference point method like that of Patton [1980], in which the spectra of nearby events in a small epicentral source region are corrected for path effects by using the propagation parameters calculated for a reference event in the region whose mechanism has been determined by other methods. Mechanisms and depths of the subsequent events can then be found through linear inversion of their path-corrected spectra. Suarez [1982] showed that mechanisms and depths of earthquakes determined from such path-corrected spectra agree well with the solutions derived from body wave modelling of the same events.

Shudofsky [1985] determined the source mechanisms and focal depths of 20 earthquakes (Fig. 1) associated with the East African rift system, these being the only events in the period 1964-1978 which were amenable to teleseismic study. These earthquake depths are the first accurately determined for a region thought to be the best example of a currently active continental rift. The mechanisms and depths of six events were determined using both long period body wave modelling and non-linear inversion of fundamental mode Rayleigh wave amplitude spectra. These were then used as master events and Patton's reference point method applied to determine the mechanisms and focal depths of other nearby earthquakes. Body wave modelling was also used to further constrain the mechanisms and depths of three of these events. The source properties of one event, for which Rayleigh records were not usable, were ascertained through body wave modelling alone.

As may be seen in Figure 1, the events do not occur in the classic rift structures of the eastern rift in Ethiopia or Kenya. Nonetheless, the normal fault mechanisms and tensional stress axis orientations of these events clearly reflect the overall extensional tectonics of the entire rift region. A histogram of focal depths for the East African events is presented in Figure 2. Depths derived with the help of body wave modelling are considered to be the best constrained, while focal depths estimated using Rayleigh spectra alone are probably somewhat less accurate. However, for each of the nine events whose depths were estimated by both body wave modelling and Rayleigh inversion methods, the two depth determinations varied by no more than 7 km, with a mean difference of 3.5 km. This suggests that we may also have some confidence in the depths determined via the path-corrected surface wave data alone. Note that the depths of the four deepest East African events were determined with the aid of body wave modelling.

These depths are unusually deep for a region of continental extension. Earthquake depths in the western U.S. Great Basin area are generally shallower than 20 km [Arabasz et al., 1980]. Chen and Molnar [1983] propose that seismicity in zones of continental extension is generally shallower than 12-15 km, with minor activity down to 20 km. They did, however, suggest that one of the events shown in Figure 2 (#16) occurred at greater depth. Shudofsky's [1985] results not only demonstrate this event's depth, but establish that 40% of the East African events studied were deeper than 15 km. We thus regard these events as 'deep' in the sense that these earthquakes are deep for a zone of continental extension or, in fact, for any continental setting outside of collision zones. We now proceed to investigate the implications of these events for the thermal and rheological structure of the rift system.

Strength Estimates

In this section we use reasonable estimates of local geotherms as derived from published heat flow measurements together with the temperature-dependent strengths of probable crustal and upper mantle materials as determined by laboratory studies to construct strength envelopes for our epicentral regions in East Africa.

The most unambiguous heat flow measurements available [Chapman and Pollack, 1977] are from Zambia near the epicenters of events 16-18. The mean surface heat flow of 66 mWm^{-2} reflects more than 350 measurements taken at eleven different sites, with individual site means ranging from 54 to 76 mWm^{-2}. As there is no volcanism or surface faulting in the area of the measurements, these values should not be unduly affected by non-conductive heat transport. Chapman and Pollack also corrected their measurements for local heat production, which was found to be significantly above the average for old continental regions, and concluded that the reduced heat flow was still unusually high for a region characterized by Precambrian surface geology. We use their measured values of surface heat flow, q_s, heat production, A_0, and thermal conductivity, α, in the solution to the one-dimensional heat conduction equation [Lachenbruch and Sass, 1977] to compute the geotherm for this region.

In constructing our strength envelopes we adopt a strain rate, ε, of $10^{-15}s^{-1}$, a value commonly used by other workers for the Basin and Range region of the western United States [e.g., Morgan et al., 1986]. Upper limits for crustal extension are estimated from geological data to be about 10 km in Kenya in the rift proper and only 2-3 km in northern Tanzania, while rift faulting in these regions began about mid-Miocene and early Pliocene time, respectively [Baker et al., 1972]. We thus consider our adopted ε to be a reasonable estimate for these regions. Many studies employing different methodologies find crustal thicknesses of 32-42 km adjacent to rifting in East Africa [e.g., Bram and Schmeling,

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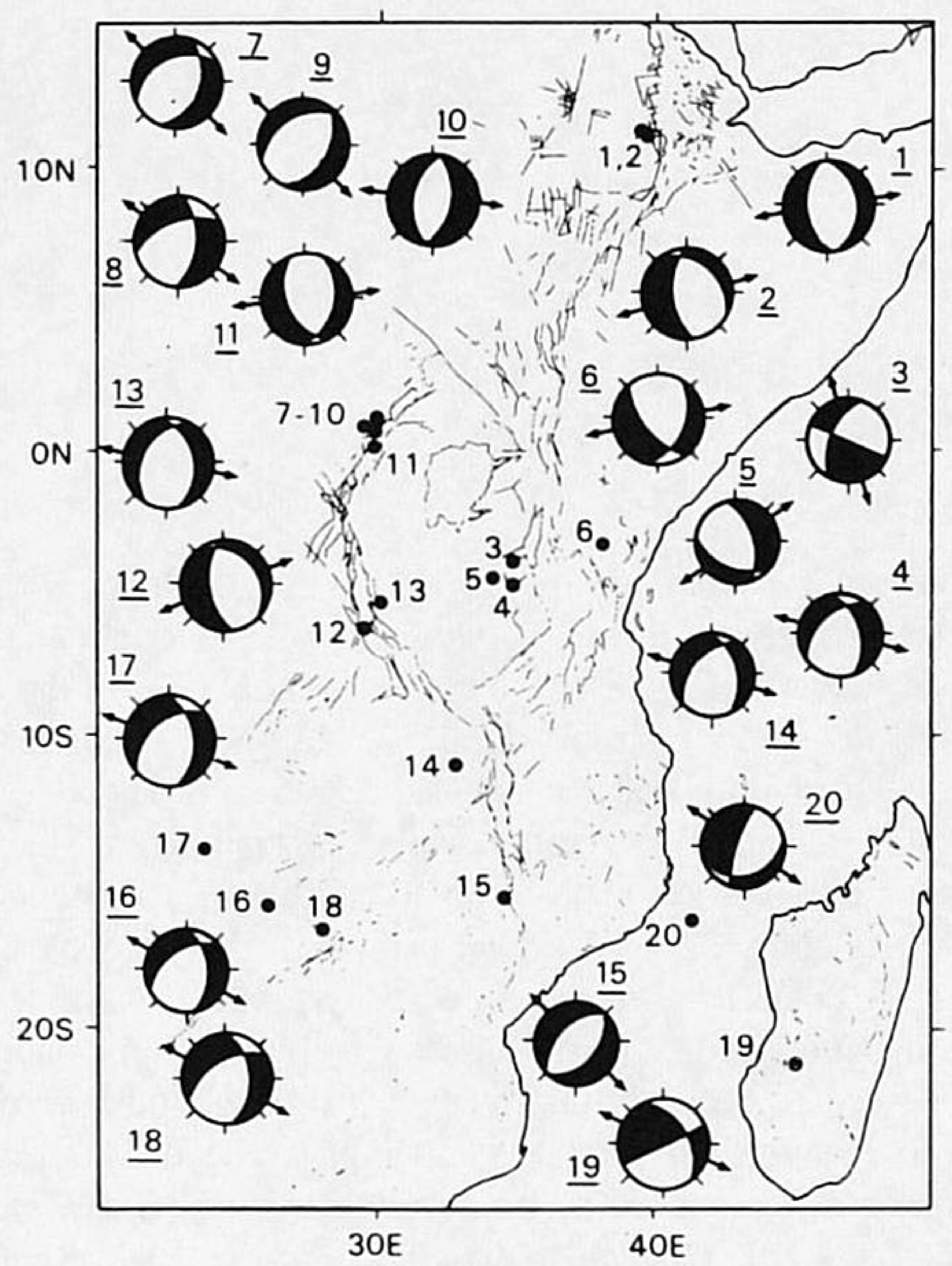

Fig. 1. Solid numbered circles represent epicenters of East African earthquakes studied by Shudofsky [1985]. For identification purposes, events are grouped into regions as follows: 1-2, Afar; 3-6, Tanzania; 7-11, Ruwenzori; 12-13, Lake Tanganyika; 14-15, Luangwa/Malawi; 16-18, Zambia; 19-20, Madagascar/Mozambique Channel. Correspondingly numbered focal plane solutions (lower hemisphere projections) give the event source mechanisms. Outward-facing arrows indicate the direction of the horizontal projection of least compressive stress axes.

1975; Bonjer, 1976; KRISP, 1987]. We thus adopt a crustal thickness of 37 km for our calculations. It is important to note that all published estimates of crustal thickness are greater than the maximum focal depths of our events, so that these are presumably occurring in the lower crust.

Shown in Figure 3 are the calculated geotherm and strength envelope for Zambia assuming an upper crust composed of quartz, a lower crust of diabase, and an olivine composition upper mantle. Brittle behavior derived from Byerlee's law follows the Brace and Kohlstedt [1980] relation while the flow law constants governing ductile behavior of the relevant materials are taken from the compilation by Smith and Bruhn [1984]. In interpreting such figures, one must bear in mind the uncertainties due to imprecise knowledge of the parameters used in the flow laws. Still, it is clear that the occurrence of earthquakes as deep as 27 km in Zambia is inconsistent with a quartz rheology, as quartz has negligible strength at these depths. A diabase composition would explain continued strength to somewhat deeper levels and may account for the deepest events, where the diabase strength is on the order of 100 MPa (1 kb). The pore pressure used in our calculations is intermediate between hydrostatic and dry; in these two extreme cases the position of the diabase brittle-ductile transition occurs only about one km deeper or shallower, respectively, for a given $\dot{\varepsilon}$. The inferred temperature at 27 km depth is about 450°C, while Chen and Molnar [1983] proposed 350±100°C as the limiting temperature for crustal earthquakes. Before we draw any conclusions from the situation in Zambia, we examine the other regions where deep earthquakes occur.

Heat flow measurements in other regions of East Africa show appreciable scatter [Morgan, 1983]. Many of the higher values, however, are associated with areas experiencing recent volcanism or at nodes where structural trends cross and groundwater circulation may cause thermal anomalies. Thus, measured q_s averages about 105 mWm^{-2} on the floor of the Kenya rift but only about 52 mWm^{-2} on the rift flanks. Observations in Lakes Tanganyika and Malawi yield q_s estimates of 22-66 mWm^{-2}, although isolated values of 100-150 mWm^{-2} have been measured near structural nodes in the lakes. The high values in the cited ranges include corrections for sedimentation and bottom-warming effects. The coastal region of East Africa has a mean q_s of about 58 mWm^{-2}. Away from local thermal anomalies, then, the other regions where deep events occur would seem to have somewhat lower heat flow than Zambia. We adopt a value of 52 mWm^{-2} as representative, but realize that the geotherm in these regions is not as well constrained as in Zambia.

Plotted in Figure 4 are the geotherm for a q_s of 52 mWm^{-2} and the corresponding strength envelope using the same $\dot{\varepsilon}$ and quartz/diabase/olivine composition as in the Zambia case. An A_0 of 2.0 μWm^{-3} has been used rather than the value of 2.4 μWm^{-3} used for Zambia, as Chapman and Pollack [1977] noted that the Zambia heat production was about 0.7 μWm^{-3} higher than the average values of 1.7 μWm^{-3} found for all continental regions and 1.6 μWm^{-3} found for the Canadian shield. Similarly, we have adopted a value of 2.5 $Wm^{-1}K^{-1}$ for α, a value used by many other workers [e.g., Lachenbruch and Sass, 1978; Morgan et al., 1986], rather than the somewhat higher value of 3.0 $Wm^{-1}K^{-1}$ found for Zambia. We have investigated the effect on the computed strength envelopes of these parameter changes, and will comment later on their importance for our conclusions.

Figure 4 shows that the 52 mWm^{-2} geotherm results in slightly deeper brittle-ductile transition depths than in the Zambia case, but we see that the important features of the strength envelope are not significantly altered. As in Zambia, the 25-29 km deep events in Tanzania, Ruwenzori, and Luangwa imply a material strength at these depths far exceeding that of quartz. Diabase would retain a strength on the order of 100 MPa at the maximum observed focal depth, similar to the value found for Zambia. The geotherm reaches 450°C at 30 km depth so that these deep events are again occurring at or near the postulated limiting temperatures for crustal material, as in the Zambia case. The inferred representative geotherm of 52 mWm^{-2} for the other areas of deep seismicity in East Africa thus gives results in agreement with those for Zambia, where the geotherm and strength envelope are much more tightly constrained.

Also shown in Figure 4 are the geotherms and strength envelopes for q_s of 38 mWm^{-2} and 66 mWm^{-2}, respectively, which represent approximate upper and lower bounds for heat flow in these regions. For a q_s of 38 mWm^{-2}, which is otherwise typical of a stable Precambrian shield, the brittle regime extends throughout the crust and into the upper mantle. Given the fact that a much higher heat flow is observed in Zambia, a region with Precambrian surface geology and no evidence of surface rifting, we consider this lower bound for q_s to be unrealistically low. At the other extreme, a q_s of 66 mWm^{-2} would predict negligible strength for diabase at the maximum observed focal depths and a temperature there in excess of 600°C, an unreasonably high value for crustal materials.

How would using the A_0 and α of the Zambia case to construct Figure 4 affect these conclusions? The resultant geotherms would be less steep, so that lower crustal and upper mantle strengths would be enhanced and the q_s = 66 mWm^{-2} case could provide strengths of about 50 MPa at 30 km depth. Temperatures there, however, would still exceed 500 °C. The q_s = 52 mWm^{-2} case would give a corresponding temperature of about 350°C, but would predict significant upper mantle strength to at least 80 km depth. Further implications of our inferred strength envelopes will be considered in the following section.

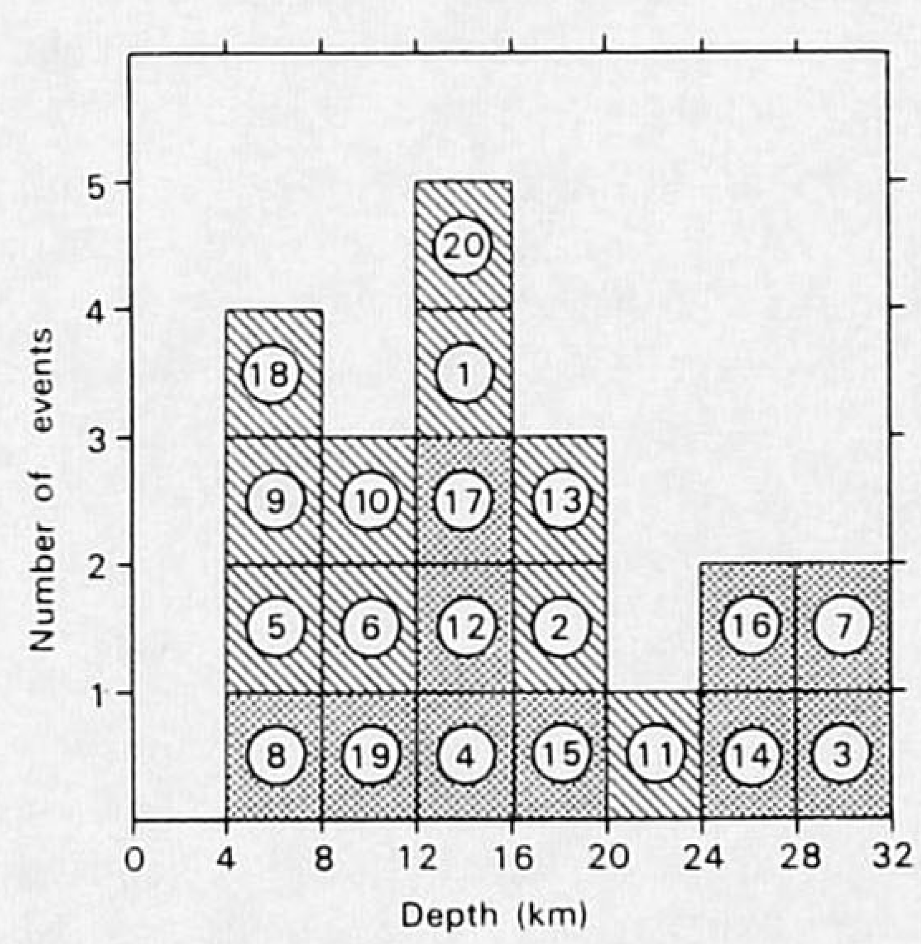

Fig. 2. Histogram of East African earthquake focal depths, compiled from Shudofsky [1985]. Circled numbers identify each event according to the numbering of Figure 1. Shaded boxes denote events whose focal depths were determined using both body wave modelling and non-linear inversion of Rayleigh wave amplitude data, with the exception of Event 7, for which body wave modelling alone was used. Hatched boxes denote events whose depths were determined via linear inversion of path-corrected Rayleigh spectra. See text for further details.

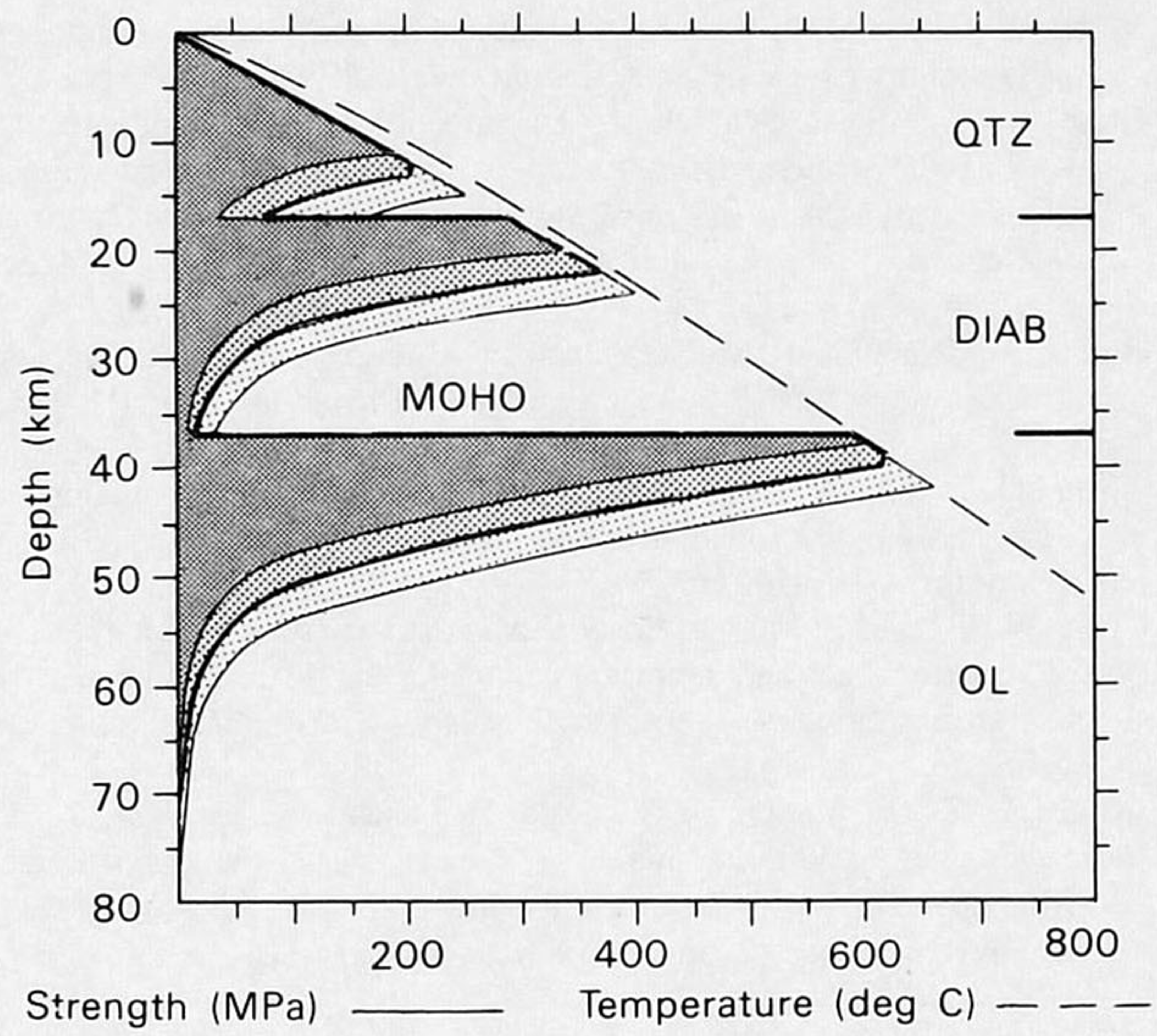

Fig. 3. Strength envelope for Zambia using $\dot{\varepsilon}$ of $10^{-15}s^{-1}$ is given by the bold line. Thinner lines above and below it denote the strength envelope for $\dot{\varepsilon}$ of $10^{-16}s^{-1}$ and $10^{-14}s^{-1}$, respectively. Shading is used to show the extent of the strength envelopes. Darkest shading fills the envelope for a $\dot{\varepsilon}$ of 10^{-16} and progressively lighter shading shows the growth of the envelope for $\dot{\varepsilon}$ of $10^{-15}s^{-1}$ and $10^{-14}s^{-1}$, respectively. Dashed line represents the geotherm used in the strength calculations, derived from measurements of Chapman and Pollack [1977]. These include a q_s of 66 mWm^{-2}, A_0 of 2.4 μWm^{-3}, and α of 3.0 $Wm^{-1}K^{-1}$.

Discussion and Conclusions

As reviewed above, Chen and Molnar [1983] conclude that crustal seismicity in zones of continental extension is mostly shallower than 12-15 km, with possible minor activity down to near 20 km. Stable continental interiors younger than 800 Ma are typified by seismicity to 20 km depth while older cratons exhibit seismicity to 25 km depth. How can these results be interpreted in light of the fact that deep events in East Africa occur at depths of 25-30 km?

We reiterate first that a quartz-rich rheology at these depths seems ruled out by the temperature and strength constraints (see Figs. 3 and 4). A mafic lower crust of diabase composition, which would display strengths of about 100 MPa at these depths, could account for the occurrence of events in the lower crust. An olivine rheology would, of course, also provide the required strengths, which would imply that these events are below the Moho. Such an explanation would have to be reconciled, however, with the fact that all crustal thickness estimates in East Africa to date are greater than the maximum observed focal depths of these events. Isolated instances of intrusion of olivine-like upper mantle material may be part of the slowly developing rifting process, but the extent to which this process may have progressed is limited by the fact that the observed geotherms are only modestly perturbed relative to those of a stable craton, so that widespread replacement of old and cold lithosphere by hotter material has not recently taken place. It is thus difficult to explain the occurrence of deep earthquakes over such a wide region of East Africa as being due to an olivine rheology at these depths.

Figure 3 suggests that a greatly increased strain rate would also lower the brittle-ductile transition depth and result in increased strength overall. As already pointed out, however, an average $\dot{\varepsilon}$ much in excess of $10^{-15}s^{-1}$ is ruled out by the geological observations in Kenya and Tanzania. Moreover, while it might be possible to invoke a locally high $\dot{\varepsilon}$ for an isolated deep focus event, the wide geographical distribution of these deep earthquakes in East Africa effectively precludes this explanation as being applicable to all the events. In addition, DeMets et al. (pers. comm., 1987) have established the relative rotation pole for Nubia-Somalia motion well to the south of Africa, so one would expect even lower spreading rates in the southerly located epicentral regions relative to the already low rate inferred in Tanzania.

Seismicity in regions of continental extension is commonly thought to be confined to the shallow crust because of locally high geotherms brought about by lithospheric (and even crustal) thinning. In contrast, the local geotherms in the epicentral regions of the deep East African earthquakes have not been unduly raised and the material at these depths retains a significant part of its strength. In this regard the areas where the deep East African events occur may be more representative of a region on the verge of rifting than of a more localized extensional setting such as the Lake Baikal, Rhinegraben, Rio Grande or Kenya rifts, which all have measured q_s of about 100 mWm^{-2} [Morgan, 1983]. This hypothesis is supported by the fact that, as noted earlier, the crust in East Africa is apparently 32-42 km thick at points within 50 km of surface rifting. The inference is that the crust, at least, is largely in the pre-rift state typified by the stable continental craton of Africa. A similar situation may exist in the Rhinegraben area, where earthquake hypocenters do not exceed 13 km depth beneath the graben proper but reach 22-24 km depth beneath the adjacent Black Forest region [Fuchs et al., 1987].

The occurrence of earthquakes in East Africa at focal depths of 25-30 km indicates that material at these depths is still strong. Our strength envelope modelling results suggest that this material must have rheological properties akin to those of a diabase or olivine. Lithospheric thinning, if it has occurred, has not proceeded to the point where the crustal geotherms are significantly perturbed. Chen and Molnar [1983] hypothesize that strain in a continent is usually absorbed by its weak, young portions so that the strain rate in the older cratons is too low to cause appreciable deep seismicity, thus accounting for the observed 20-25 km maximum depth of earthquakes in cratons. The occurrence of deeper events in East Africa might then be taken as evidence for the existence of a condition sufficient to account for the increased strain rate and, ultimately, for the rifting itself.

If a stress level sufficient to result in lower-crustal earthquakes is operative in East Africa, then we may well wonder why no deeper events are seen in the upper mantle, where an olivine rheology predicts regions of high strength (see Figs. 3 and 4). Any rifting process which results in high stress levels in the crust should affect the upper mantle below the crust as well. The absence of even deeper events suggests that material strengths in this region, expected to be controlled by an olivine-like

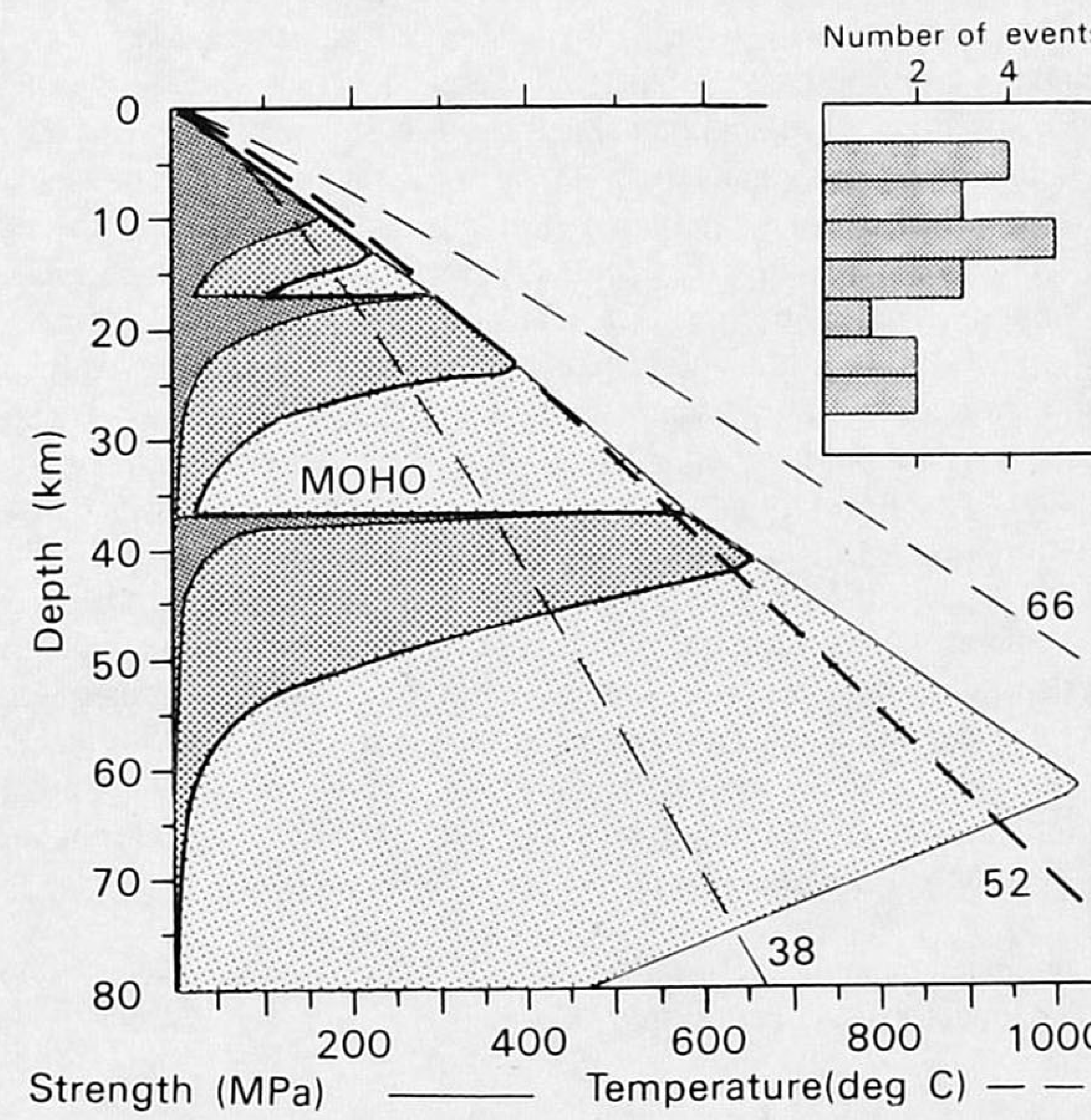

Fig. 4. Strength envelope for other regions of deep seismicity in East Africa. $\dot{\varepsilon}$ is $10^{-15}s^{-1}$. Bold line is for q_s of 52 mWm^{-2}, taken as representative for these regions. The thinner lines denote the strength envelopes for q_s of 66 mWm^{-2} and 38 mWm^{-2}, respectively, which represent approximate upper and lower bounds for q_s. Darkest shading fills the envelope for q_s of 66 mWm^{-2}, while progressively lighter shading shows the growth of the envelope for q_s of 52 mWm^{-2} and 38 mWm^{-2}, respectively. Dashed lines labelled with q_s values denote the geotherms for the three cases. A_0 is 2.0 μWm^{-3} and α is 2.5 $Wm^{-1}K^{-1}$. Inset to upper right is a histogram of the earthquake focal depths.

rheology, cannot be as high as an extrapolation of the measured surface geotherms would indicate. The high A_0 and α values measured and used for Zambia (Fig. 3) result in a relatively less steep geotherm and less rapid falloff of material strength with depth. In terms of strength, we have been conservative in using lower values for A_0 and α in constructing Figure 4 for the other regions of deep seismicity. The use of the Zambia values, which are the only local measurements available in our epicentral regions, would even further enhance the lower crustal and upper mantle strengths. An upper mantle rheology controlled by materials weaker than olivine is of course a possibility, but such a weak zone would have to be both locally thick and extremely widespread geographically to explain negligible upper mantle strength in all the regions where deep events occur in East Africa.

A thermal anomaly in the upper mantle could account for the observed focal depths of East African earthquakes. Heat transfer by conduction is a slow process, with time scales on the order of tens of millions of years required for a deep temperature anomaly to result in marked surface temperature gradient perturbations [Chapman and Pollack, 1977]. This effect is demonstrated along the Hawaiian-Emperor chain, where the maximum heat flow does not occur at Hawaii, the present location of the active hotspot marked by volcanism. This observation is interpreted as showing that reheating occurring at Hawaii, at a depth of approximately 50 km, gives rise to the observed uplift almost simultaneously, whereas a finite conduction time is required for the thermal anomaly to manifest itself at the surface. In fact, since earthquakes beneath Hawaii occur to a depth of almost 50 km [Butler, 1982], the reheating event at Hawaii must have taken place quite recently and not yet markedly reduced the rigidity of the lithosphere.

Given the emplacement of a thermal anomaly beneath East Africa at an appropriate time in the past, we can envision a present-day situation characterized by a crustal geotherm which is still relatively low, so that considerable strength is retained and earthquakes can occur deep in the crust. The upper mantle, meanwhile, may have warmed to the point where its strength has been reduced and seismicity thereby suppressed. We emphasize that such an explanation of the observed earthquake focal depth distribution in East Africa is not a simple case of "fortunate timing". In fact, such a situation might be expected to arise and persist for geologically meaningful periods of time as part of a dynamic rifting process whose time scale is governed by the rate of heat conduction.

Shudofsky [1985] has demonstrated the existence in East Africa of a consistently oriented regional tensional stress field which extends over a wide geographical region and over a range of focal depths. An extensive and deep-seated thermal anomaly could be consistent with such a stress field while also explaining the fact that the surface geotherms are raised only slightly relative to those of a typical Precambrian craton. As outlined above, this would also account for the observed earthquake focal depth distribution. The presence of such a deep-seated anomaly is supported by recent work [Shudofsky, in prep.] involving the inversion of Rayleigh wave phase velocity measurements in East Africa, which suggests the presence of an anomalous low-velocity zone at depths of 75-175 km beneath the Eastern branch of the rift system which extends to the southwest beneath regions which are seismically active but have not experienced recent surface rifting or volcanism. Taken together with thermal and rheological constraints on the crustal and shallow mantle structure derived from the earthquake focal depth and simple strength envelope considerations presented here, such seismological information may yield new insight into the process of continental rifting.

Acknowledgements. Partial support for this work was provided by a NATO Postdoctoral Fellowship (to G.N.S.) and by NATO grant 0148/87.

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(Received February 26, 1987:
accepted May 1, 1987.)