PERGAMON

Journal of Asian Earth Sciences 19 (2001) 249–256

Journal of Asian Earth Sciences

www.elsevier.nl/locate/jseaes

Southern Tibet: its deep seismic structure and some tectonic implications

O. Kola-Ojo[1], R. Meissner*

Institute of Geoscience, Kiel University, D-24098 Kiel, Germany

Received 28 April 1999; revised 21 February 2000; accepted 7 July 2000

Abstract

An international seismic investigation in southern Tibet, the INDEPTH (International Depth Profiling of Tibet and the Himalayas) II project, was conducted in 1994. The German contribution, GEDEPTH (German Depth Profiling of Tibet and the Himalayas), included broad-band seismometers and 30 mobile seismic stations. These stations were situated in the area of the Yarlung Tsangpo Suture and recorded signals up to a distance of 250 km from shots along the INDEPTH II reflection line. Velocity information from an offset-dependent travel time diagram revealed a 35 km thick (sialic) upper crust with V_P below 6.3 km/s, including a low-velocity-channel between 15 and 20 km depth. V_P-values in the lower crust are not well constrained, but some events with an 8 km/s velocity were recorded from a depth of around 70 km. They are only observed between 240 and 250 km distance. This short offset range does not allow a decision on whether they are P_n or P_MP, or diving waves from a velocity gradient zone at the base of the crust. Several observations argue for a velocity gradient zone, compatible with the presence of a smooth gabbro-eclogite transition. Also a temperature model of southern Tibet is presented, which is based on certain boundaries of heat flow models, P- and S- velocities, surface waves, and seismicity. Based on our velocity and temperature models, an assessment on the petrological and rheological structure for the evolution of the Tibetan plateau was made. Among the four most viable models we prefer the "Hydraulic Pump" model, supported by crustal "Escape" and mantle "Underthrusting". © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Seismic structure; Velocity information; Tectonic implications

1. Introduction

It has become widely accepted that the Himalayan mountain range and the Tibetan plateau are the products of a collision between the Indian subcontinent and the Asian continent, a process which is still going on today (Dewey and Bird, 1970; Molnar and Tapponnier, 1975; Tapponier et al., 1981; Wang et al., 1982; Zhao et al., 1993, 1997]. The 3500×1500 km^2 Tibetan plateau with its relatively uniform elevation of about 5 km is one of the most outstanding topographic features on earth. However, the mechanism of the broad and uniform regional uplift is still hotly debated.

About 40–50 Ma ago the Indian subcontinent collided with Asia, and since that time the rate of convergence has decreased from more than 10 cm per year to presently 5 cm per year (Molnar and Tapponnier, 1975). As a consequence of the strong (intercontinental) convergence rate, ample stacking and shallow angle thrusts developed in the Himalayan mountain belt (Dewey and Burke, 1973). Early wide-angle-seismics, e.g. data from fan shooting, indicated a crustal depth of more than 70 km in southern Tibet (Wang et al., 1982; Hirn and Sapin, 1984), but information on crustal structure and interval velocities from these transects was limited (Gongjian et al., 1990). There is a N–S shortening of several hundred kilometers in the Himalaya and a W–E extension in Tibet, as seen from focal plane solutions and geologic mapping, first recognized by Molnar and Tapponnier (1975). Later the names "Extrusion" or "Escape-Tectonics" (Burke and Sengör, 1986) developed for the E and SE "escaping" Tibetan units (England and Houseman, 1989; Bird, 1991). The impact of the Indian collision is not concentrated on a sharp boundary, as known from oceanic plate boundaries, but extends to the whole Tibetan Plateau.

The apparent doubling of crust in Tibet is still a mystery (Ratschbacher, 1996). It seems that the Indian lithosphere, including parts of the crust, was underthrust beneath the Tibetan crust and has contributed to the crustal doubling. This follows from seismological studies (Barazangi and Ni, 1982), from an early Chinese gravity model and recently

---

* Corresponding author. Tel.: +49-431-880-3908; fax: +49-431-880-4432.

E-mail address: rmeissner@email.uni-kiel.de (R. Meissner).

[1] Present address: 807 909, 7th Avenue SW, Calgary, Alberta, Canada T2P 1A6.

1367-9120/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S1367-9120(00)00041-9

from the INDEPTH II results (Nelson et al., 1996), including the results from the seismic broad-band stations (Kind et al., 1996; Yuan et al., 1997). Rheologically, the emplacement of the Indian lithosphere below the Tibetan crust — not the Tibetan lithosphere — was always hard to understand. Given the known convergence rate, the Indian lithosphere should have travelled more than 2000 km to the north. This is definitely not the case. We can observe high P_n — and high S_n — velocities and a considerable thickness of the subcrustal lithosphere, but the extension of this lithosphere to the north is only observed about 360 km, i.e. it reaches the area of the Bangong–Nuijang Suture in the middle of Tibet (Barazangi and Ni, 1982; Beghoul et al., 1993) (Fig. 1). This means that the Indian subcrustal lithosphere must either have been broken and shortened on its way, and/or has disappeared by delamination.

There are many evolutionary models proposed for the Tibet plateau, e.g. Dewey and Burke (1973), Barazangi and Ni (1982), Zhao and Morgan (1985, 1987), Wernicke (1990), Bird (1991), Westaway (1995). Beghoul et al. (1993) have reviewed the four main models. They cite first the “escape model” (Molnar and Tapponnier, 1975; Tapponnier et al., 1990). It is proposed that most of the S–N shortening is absorbed by large horizontal W–E motions of hundreds of kilometers along mega-strike-slip faults such as the Altyn Tagh and Kun Lun faults (in the E and NE, outside the area of Fig. 1). This mechanism leads to an eastward extrusion of the Tibetan lithosphere. The model is supported by recent studies of shear wave splitting (McNamara et al., 1997). Next, there is the “hydraulic pump model” (Zhao and Morgan, 1985, 1987), recently revived by Westaway (1995). In this model, the underthrusting Indian crust acts like a piston of a hydraulic pump, where the fluid component is the weak lower Tibetan crust. This model implies a rather uniform uplift of the plateau. It is compatible with the uplift history, with the recent seismological detection of a fluid-like middle crust (Nelson et al., 1996) and with our temperature model. Next, the “underthrust model” going back to Argand (1924) is supported by new seismological studies (Barazangi, 1989; Beghoul et al., 1993). It proposes underthrusting of the Indian continental lithosphere beneath the former Tibetan Moho, leading to a doubling of the crust. This mechanism seems to be plausible, at least for southern Tibet with its overthickened crust of more than 70 km and a subcrustal (Indian) lithosphere of at least 100 km thickness. Finally, the “accordion model”,

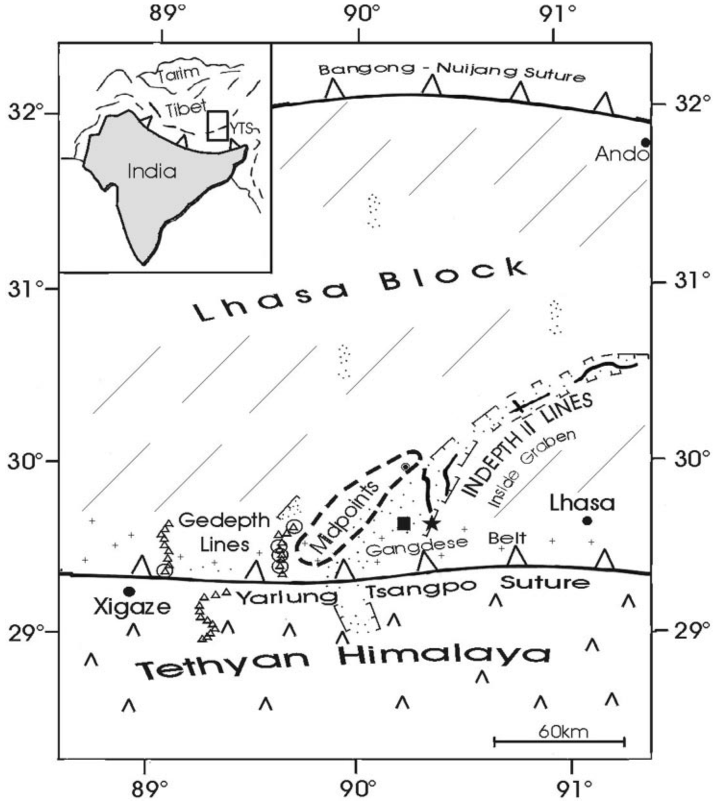

Fig. 1. Locations of INDEPTH II and GEDEPTH profiles (small triangles) and simplified geology of southern Tibet after Dürr (1993); Tapponnier et al. (1981). *From south to north:* the Tethyan Himalaya, consisting of thick limestone, sandstone and shale deposits. The Gangdese batholith, an intrusion into the Lhasa block, is made up of diorites and granodiorites. The rest of the Lhasa block consists of Precambrian two-mica gneisses covered by some shallow marine sediments. The Yarlung–Tsangpo and the Bangong–Nuijang sutures are outlined by ophiolites. Young N–S or SW–NE directed extensional grabens are marked by small dots. The shaded square and star denote the broad-band location A 36 (used in comparison with our velocity model) and the INDEPTH II reflection station (used in picking the P_g arrivals for the first 60 km offset of our velocity model of Fig. 3), respectively. The midpoint locations of the wide-angle data are outlined between the GEDEPTH and INDEPTH II lines, the midpoint for the 250 km Moho event is marked by a circle.

first studied by Dewey and Burke (1973), later by England and Houseman (1986) and Gongjian et al. (1990), suggests that the S–N shortening is absorbed by diffuse thickening of the Tibetan lithosphere. All these models might overlap or dominate in certain time intervals.

Today's crustal thickness of southern Tibet and here especially in the southern Lhasa Block (Fig. 1) was revealed clearly by the INDEPTH I and II data, i.e. from Common Mid Point (CMP) and wide-angle reflection work (Zhao et al., 1993; Nelson et al., 1996), including our data, and from receiver functions, obtained from 15 broad-band stations of the GEDEPTH program (*Ge*rman *De*pth *P*rofiling of *T*ibet and the *H*imalaya) (Kind, 1996; Yuan et al., 1997). Our studies in this paper concentrate on the signals recorded by GEDEPTH's 30 seismic stations across the Yarlung Tsangpo Suture (Fig. 1), recording arrivals from shots along the CMP line, i.e. wide-angle observations in the "piggy back" mode. The data were first used for filling in the gap of the CMP line across the Yarlung Tsangpo Suture, using move-out corrections to make them compatible with the INDEPTH II CMP — recordings (Husen, 1995; Zhao et al., 1997). For the wide-angle interpretation, only five of our fixed stations recorded clear signals from the shots along the INDEPTH II line toward the NE. They were used for the development of velocity depth models, one of the main subjects of the present study. In addition, an assessment of the temperature is presented which — together with the seismic model — is used to select between the four main evolutionary models of southern Tibet (Beghoul et al., 1993).

2. Seismic and seismological models for southern Tibet

Thirty mobile seismometers were installed 100–150 km west–southwest of the INDEPTH II reflection line in the area of the Yarlung Tsangpo Suture (YTS) to record seismic signals from the reflection shots, up to 250 km to the NE. The data was used to obtain a composite record section. This section is based on five selected geophones (the selected geophones are circled in Fig. 1) with strong signal to noise ratios and on signals from all the shotpoints along the INDEPTH II line. Fig. 2 shows the composite record section scaled with offset with some arrivals marked after editing, field statics, band-pass filtering (between 2 and 10 Hz), binning (bin size was 400 m), residual statics, and vertical or offset stacking (average fold was 5). Although there are many gaps in the recordings and explosions were fired along a slightly crooked reflection line, the record section provides a basis for assessing a one-dimensional (1D) velocity–depth model and for comparing it with the data from the receiver functions in this area. As no reverse shooting is available horizontal layering or a very small NE-dip of crustal layers was assumed, based on the INDEPTH I and II reflection data. The arrivals from the mantle are very clear but are observed only in an offset between 240 and 250 km, and no data from 215 to 240 km or beyond 250 km were recorded. Hence, some uncertainties remain, especially for the lower crust and the uppermost mantle.

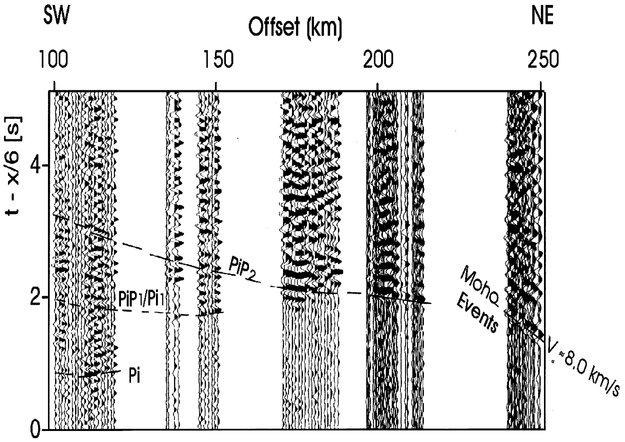

Fig. 2. The composite (1D) seismogram section from 100 to 250 km offset, reduced with 6 km/s. Picked arrivals are connected by weak correlation lines, used for generating the velocity model of Fig. 3. P_i = midcrustal refraction from bottom of layer 1; P_iP_1 = midcrustal reflection from bottom of layer 3; PiP_2 = midcrustal reflection from the bottom of layer 4 (Fig. 3). The reference or pilot trace obtained by correlating all the traces within a bin, is correlated with the individual traces to estimate and effect the statics with a maximum allowable shift of 100 ms. The seismic wide-angle data was processed on a Unix Workstation with the FOCUS processing package of the Cogniseis Development Inc. and presented as wiggle-trace variable-area plots using the Seismic Unix (S.U.) package (Cohen and Stockwell, 1997).

Our proposed 1D velocity–depth model was obtained by using the 2D inversion ray-tracing and synthetic modelling program of Zelt and Smith (1992) and Zelt and Forsyth (1994). Discussing the best fitting velocity–depth model (Fig. 2) from top to bottom, there are "sialic" velocities with $V_p < 6.3$ km/s down to about 35 km depth, including a clear low-velocity-channel between 15 and 20 km depth. Below 35 km depth no direct velocity information data are available, but at an offset of 240–250 km we recorded velocities of more than 8 km/s from a depth of at least 70 km. A decision about the wave type is difficult, because at these large distances P_MP, P_n, and diving wave phases have nearly the same traveltimes and apparent velocities. From the three possibilities (P_MP, P_n, or diving waves), we consider diving waves as the most probable solution, based on four arguments.

1. From the synthetic modelling of the different phases, it is not likely that these far-offset events are P_MP because not any signs of such arrivals are observed in the subcritical range (see Fig. 3).
2. Diving waves, on the other hand, do not produce any signals below the critical angle, which is compatible with the observations and the modelling (see Fig. 4).
3. Below about 60 km depth, a transition from gabbroic to eclogitic metamorphic facies takes place under appropriate conditions (Mengel and Kern, 1992; Fountain

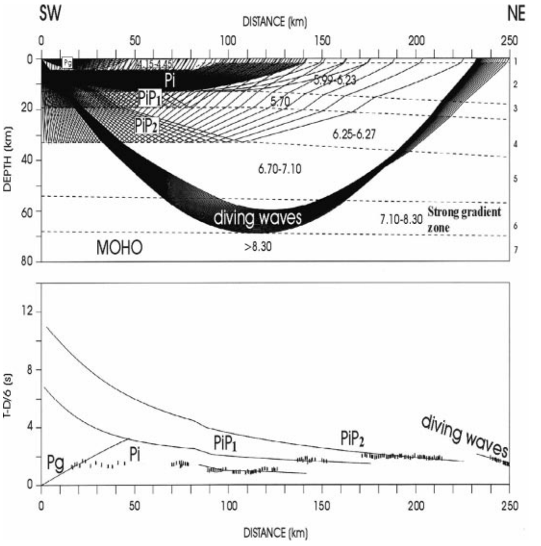

Fig. 3. (Top) The generated velocity model and ray diagram with velocities in km/s. P_g = direct arrivals; P_i = midcrustal refraction from bottom of layer 2; P_iP_1 = midcrustal reflection from bottom of layer 3; PiP_2 = midcrustal reflection from the bottom of layer 4. The Moho events have been modelled as diving waves from a strong-gradient zone, using the Seismic Unix (S.U.) package. The values within the model are the velocities in km/s from top to bottom of each layer. (Bottom) Reduced travel time diagram. Observed data: small bars. Continuous lines: traveltime branches (velocity model).

and Christensen, 1989; Fountain et al., 1994). This transition is not stepwise and may result in a smooth gradient zone in seismic velocity and density, generating diving waves (Kern et al., 1996).

4. The V_s-velocity depth functions from the broad-band stations also indicate a gradient zone rather than a strong first-order boundary (Yuan et al., 1997).

We therefore prefer the diving wave model. We have compared it with the model from the nearest receiver functions, A36 from Yuan et al. (1997), after converting our V_P data to V_S, using a Poisson's ratio of 0.29. Rodgers and Schwartz (1997) have considered this value probable for southern Tibet. Fig. 5 shows this comparison which seems to be quite satisfactory, although there are some differences in the models, e.g. differences in thickness of the low-velocity channel and Moho depth. For the lowermost crust, the receiver functions give slightly lower velocity values than estimated from the wide-angle measurements and show another (weak) boundary. These differences of the V–z curves might result from the use of different wave types (P versus S), from Poisson's ratio other than 0.29, and/or from a slightly different location of the reflection points at the Moho. But in general the crustal velocity structure in southern Tibet seems to be rather well established. The Moho appears in both our wide-angle studies and seismological receiver functions as a weak boundary towards the mantle with a velocity of more than 8 km/s.

3. Geothermal studies

There are extremely high heat flow density values q_0 in southern Tibet (Yaolin and Yuanqing, 1993; Jiyang et al., 1996). Although the scatter is rather high, q_0-values between 100 and 330 mW/m^2 are often found. In addition, hot springs, geysers, and some geothermal plants indicate a hot subsurface. Considering the high uplift rates and a strong denudation of about 10 km during the last 10–12 Ma (Xiao and Li, 1996), the eroded surface layers have been gradually replaced by hotter material from the subsurface. The high q_0-values, hence, may indicate mainly a strong geothermal gradient near the (cool) surface. They have not been used for a thermal modelling.

Several steady state temperature models between 60 and 0 Ma have been assessed by assuming an initial q_0 of 60 mW/m^2 and a 35 km thick crust. The thickening of the crust from 35 to 70 km has been considered mainly to be caused by a compressional thickening and mixing of crustal material, although other reasons like phase transitions gabbro-granulite are also considered (Henry et al., 1997; Le Pichon et al., 1997). About 10 km uplift with denudation has been assumed. The outcome of this assessment is a rough temperature–depth model (Fig. 6) which follows a "normal" geotherm (Chapman, 1986) of 80 mW/m^2 in the upper crust, neglecting the high, observed q_0-values supposed to be restricted to the surface layers.

Realizing that the temperature assessment from the mixing approach might not be reliable we looked for other constraints from velocities and seismicity. One argument is the presence of shallow seismicity in southern Tibet down to 18 km (McNamara et al., 1995, 1997). This means that for sialic material at this depth the temperature must be below about 350°C while at 20 km it must exceed this value (Meissner and Strehlau, 1982) (see curve a in Fig. 6). Another (upper) limit for the temperature at this depth is provided by the low velocity layer. Attributing the low velocity to a 10% reduction by temperatures around 450° (Kern and Richter, 1981; Kern, 1982) we get an upper limit as an average for the low velocity layer (curve b in Fig. 6). Although the assumption of this upper limit seems to be a rather weak argument, we consider it to be an average value in view of the possible magma chambers or hot brines at about these depths (Nelson et al., 1996; Makovsky and Klemperer, 1999). As a consequence, the true temperature in the upper crust should be somewhere between the two limits and supports our assessment that the geotherm follows the standard geotherm of 80 mW/m^2 (Chapman, 1986) which is quite a common value for many young mountain belts.

There are again some earthquakes in the mantle below 80 km depth (McNamara et al., 1997). They provide another (upper) limit for the temperature at these depths, because ultramafic mantle material acts in a brittle way only up to a temperature of 750°C (Parsons and Sclater, 1977). An additional argument for a cold and brittle mantle below southern

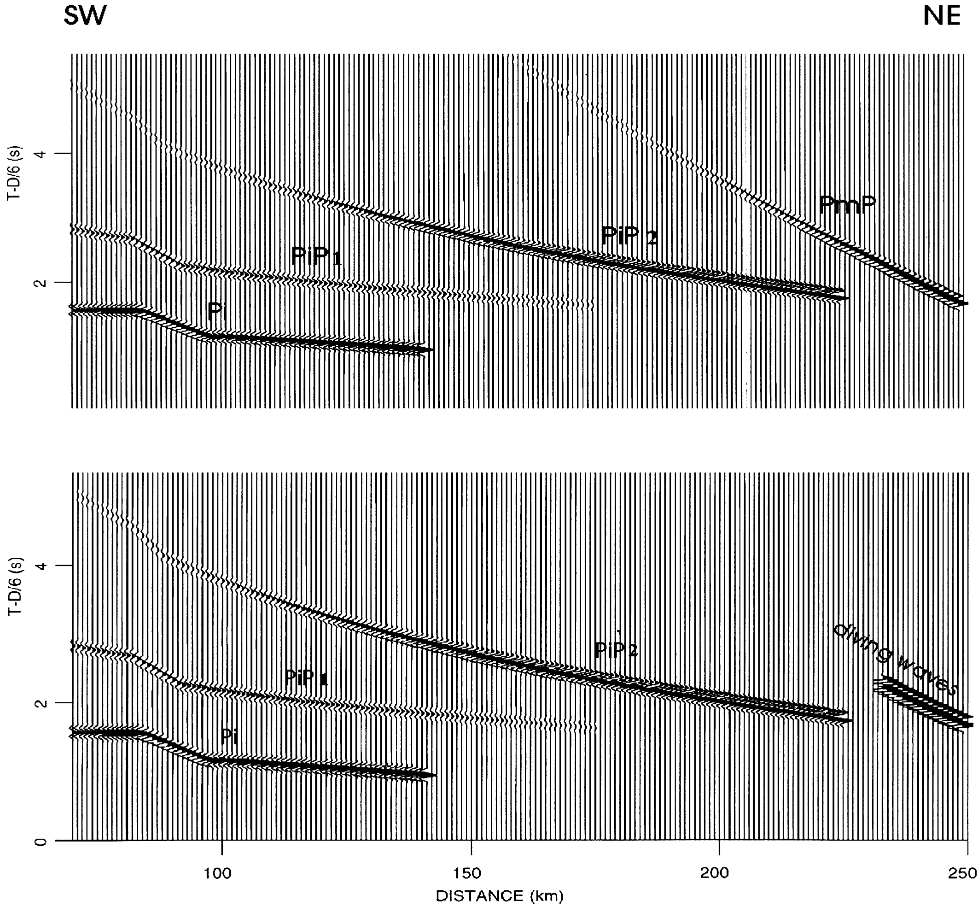

Fig. 4. Computed synthetic seismogram sections, modelling the Moho events as wide-angle reflections (P_mP), (top) and as diving waves originating from the velocity gradient zone at the bottom of the crust (bottom). The assumed attenuation (*Q*) were 200, 500, 300 and 800 for layers 1, 2, 3 and lower layers, respectively. Please note that the absence of Moho events (diving waves) at any smaller offsets provides an argument for the presence of a gradient zone.

Tibet is high mantle P_n-velocities (Barazangi and Ni, 1982) which are never found in other high heat flow areas. Hence, we have to postulate a relatively cold mantle, very probably the (still) cold Indian continental mantle pushing into Tibet.

It should be mentioned, however, that our knowledge of the temperature in the lower crust is extremely limited. Probably, a huge part of the present Tibetan crust is originally "Indian" and was transported into Tibet together with the Indian mantle, having created most of the uplift, plus a certain contribution of the postulated phase transition eclogite-granulite (Sapin and Hirn, 1997). Their thermal model — although based on different assumptions — is similar to ours. A new analysis of surface waves in southern Tibet, north of the Yarlung Tsangpo Suture (Cotte et al., 1999) shows a broad shear wave minimum around 50 km depth. If related to temperature, this depth marks the temperature maximum, exceeding even the solidus of gabbroic material (Fig. 6), supporting the assumption of Le Pichon et al. (1997), Nelson et al. (1996) and Brown et al. (1996) that a "fluid-like middle/lower crust", is present in the southern Lhasa Block, certainly with a high percentage of partial melt and apparently on top of the cold (intruding) Indian mantle. Hence, we estimated our final geotherm by following the thermal gradient a little in the upper crust and reach a thermal maximum somewhere in the lower crust around 50 km before inverting the thermal gradient slightly in order to reach the cold Indian mantle (Fig. 6).

4. Discussion

From our *seismic model* a rough estimate on the crustal petrology could be performed, showing a sialic upper crust down to 35 km (the average depth of continental crust worldwide), underlain in the southern Lhasa Block by a granulitic or gabbroic lower crust, which below 60 km depth probably has formed a smooth transition zone to an eclogitic/ultramafic mantle at a depth of more than 70 km. From the *thermal model* which is based on the boundaries of seismicity, a relatively warm crust on top of a cold mantle is revealed. In the upper middle crust the observed four very strange and strong clusters of reflections, argue for magma chambers or hot brines, and also our model and other approaches (Henry et al., 1997) show the temperature to exceed the solidus of geissic-granitic and even that of

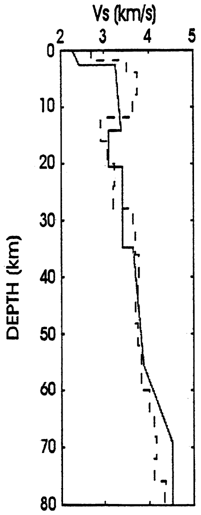

Fig. 5. Comparison of our velocity model (continuous line) with the 1-D receiver function of the nearby broad-band station A 36 of Yuan et al. (1997) (dashed line). Conversion from V_p to V_s was done with $\sigma = 0.29$ (Rodgers and Schwartz, 1997).

gabbroic and granulitic material which makes the material very weak.

This weak and even fluid-like crustal material in the middle and probably in the lower crust below southern Tibet certainly supports the "Hydraulic Pump" model of Zhao and Morgan (1985, 1987), at least for the recent tectonic development. The piston seems to be provided by the cold Indian lower crust and mantle. This "piston" acts in a slightly different way than a tectonic "indenter", found in many compressional belts, e.g. in the Alps (Pfiffner, 1991). Such an indenter is always harder (and often older and colder) than that of the indented (younger and weaker) material (Meissner and Mooney, 1998). The indentation at depth may be the main ingredient of crustal thickening in orogenic belts. But in Tibet the target of the indenter is fluid-like crustal material and its compression by a "piston" seems to be a more appropriate expression. As mentioned before, it explains the extremely wide and large, rather homogeneous uplift of the Tibetan Plateau which would certainly be much more irregular, ruptured, narrower or slanted, if solid compression and a normal indentation would prevail.

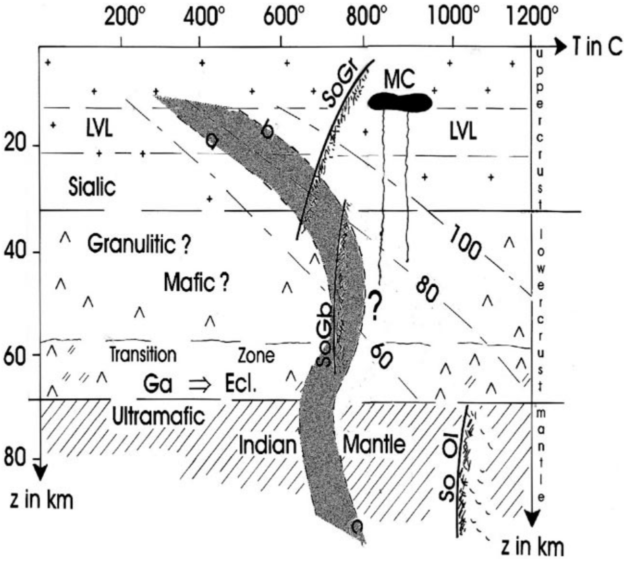

Fig. 6. Temperature assessment for crust and uppermost mantle below Tibet. a = lower limit from seismicity (no rupture for temperatures above 400°C); b = upper limit from assuming thermally reduced V_p and V_s values in Low Velocity Layer (LVL); c = upper limit for ultramafic mantle material, no rupture for temperature above 750°C and high V_p and V_s velocities (P_n, S_n) (McNamara et al., 1997); MC = bright spots = possible Magma Chambers or hot brines; 60, 80, 100 = conventional geotherms (Chapman, 1986) for heat flow values $q_0 = 60, 80, 100\ \mathrm{mW/m^2}$; SoGr, SoGb, SoOl = solidi for granite, gabbro and olivine, respectively.

Hence, it seems that the "Hydraulic Pump" model is strongly supported by the observations of the Tibetan uplift and by our seismic and thermal models. They explain nicely the present stage of the evolution of the Tibet Plateau. But the crust in Tibet was not always so thick and fluid-like as today. Other mechanisms, other models must have been dominated in the past. It is well known that in the time before the Indian–Asian collision, about 50 Ma ago, other terranes from Gondwanaland and even from Rodinia had arrived at the Asian continent in the Mesozoic and Paleozoic and had docked to the Asian mainland (Dewey and Burke, 1973; Ratschbacher, 1996). The whole area of the present day Tibet was tectonically reworked and compressed several times by a process which might be explained better by the accordion model (England and Houseman, 1986, 1989].

Other processes, described by various models are still working today. The "Underthrust" model (Barazangi and Ni, 1982) is one of them if we apply it to the *deep* intrusion of the cold Indian lowermost crust and mantle, as we observe it by our seismic and thermal models. Together with the "Hydraulic Pump" model the underthrusting mantle and some transition material provides the "piston" of the pump for the evolution of the Tibetan crust. As mentioned before, it seems strange that the Indian subcrustal lithosphere presently is observed (by refraction seismics and seismology) only up to the middle of Tibet (Beghoul et al., 1993) while according to the long-time and strong convergence rate it should have progressed very much farther to the north. Several alternatives are offered for the limited progress of the Indian subcrustal lithosphere. (1) It was probably somehow shortened or broken on its way northward, (2) it was delaminated (after a previous subduction of the oceanic lithosphere) at the YTS or/and (3) at the Bangong–Nuijang Suture in the middle of Tibet. Both sutures show ample traces of ophiolites (Wang et al., 1982; Yaolin and Yuanqing, 1993). Also (4) a lateral deviation or delamination of the Indian mantle could have occurred in southern Tibet. This last possibility is supported by recent S_n-wave studies, which show a change from S–N to W–E of the fast anisotropy axis (McNamara et al., 1997). If we believe that the bending of the fast axis and its amplitude increase in the middle of Tibet is due to some "flow lines" in the mantle, the problem arises why the upper crust and the upper mantle follow a similar bend to the east if the middle and lower crust is weak and decoupling. It seems that the escape concept (Burke and Sengör, 1986) is not restricted to the crust but effects all weak parts of the lithosphere (Meissner et al, in preparation).

So far the unusual thickening of Tibet was considered to be the main reason for the "eastward escape" Molnar and Tapponnier, 1975; Bird, 1991), a theory which was supported for the near surface by large and rather young W–E strike slip faults, by some S–N extensional faults in southern Tibet (Westaway, 1995), and by many (shallow) focal plane solutions which turn from S–N compression in the Himalayas to a dominating W–E extension in southern Tibet (Barazangi and Ni, 1982). This means that apparently a large part of the S–N convergence is guided into a W–E direction. The problem whether only the upper crust is guided eastward or the whole lithosphere is still an open question. The assumed gabbro-eclogite transition of our seismic model at the base of the thick crust causes a gravitational instability and would favour delamination (downward), especially below the weak and decoupling middle and lower crust (Meissner and Mooney, 1998). We believe that the unusually strong and continuous convergence has not only caused the high elevation of Tibet (by hydraulic pumping), but may even have generated a cyclical or repeated delamination.

5. Conclusions

Based on our seismic and thermal models, some consequences for the evolution of the Tibetan plateau have been discussed. The mentioned four evolutionary models have either dominated at certain time intervals or presently support each other. The "Accordion" model was certainly active in the early stages of crustal thickening and shortening. For the present time, we prefer the "Hydraulic Pump" model, based on our thermal, seismologically controlled, model. It is compatible with a warm and weak middle and lower crust and with various observations of the strong and rather homogenous uplift of the whole plateau. The "Hydraulic Pump" and the "Escape" models, which seem to be a consequence of the very thick and weak middle and lower crust, fit perfectly together. At depth they are supported by the intrusion of the Indian subrustal lithosphere plus some transitional material from the crust–mantle region. This is a (slightly modified) "Underthrust" model. In addition, our seismic and thermal modelling argues for delamination, preferably downward, but possibly also oblique and/or lateral. Such delamination processes may also solve the range problem of the northward-directed continuous and strong push of the Indian continent.

Acknowledgements

We thank our colleagues from the INDEPTH Team, Zhao Wenjin, Larry Brown, Doug Nelson, and Lothar Ratschbacher and from the GEDEPTH working group, Rainer Kind, Xiaohui Yuan, Friedemann Wenzel and Jim Mechie for exciting discussions and encouragement. The stimulating comments of the referees Simon Klemperer and Hans Thybo are greatly acknowledged.

References

Argand, E., 1924. La tectonique de l'Asie. Int. Geol. Cong. Rep. Sess. 13 (1), 170–372.

Barazangi, M., 1989. Continental collision zones: seismotectonics and crustal structure. In: James, D.H. (Ed.), The Encyclopedia of the Solid Earth Geophysics. Van Nostrand Reinhold, New York, pp. 58–75.

Barazangi, M., Ni, J., 1982. Velocities and propagation characteristics of Pn and Sn beneath the Himalayan arc and Tibetan plateau: possible evidence for underthrusting of the Indian continental lithosphere beneath Tibet. Geology 10, 179–185.

Beghoul, N., Barazangi, M., Isacks, B.L., 1993. Lithospheric structure of Tibet and western North America: mechanisms of uplift and a comparative study. J. Geophys. Res. 98, 1997–2016.

Bird, P., 1991. Lateral extrusion of lower crust from under high topography. J. Geophys. Res. 96, 10275–10286.

Brown, L.D., 1996. Bright spots, structure, and magmatism in southern Tibet from INDEPTH seismic reflection profiling. Science 274, 1688–1690.

Burke, K., Sengör, C., 1986. Tectonic escape in the evolution of the continental crust. In: Barazangi, M., Brown, L. (Eds.), Reflection Seismology: the Continental Crust, AGU Geodynamic Ser., vol. 14, pp. 41–53.

Chapman, D.S., 1986. Thermal gradients in the continental crust. In: Dawson, J.B, Carswell, D.A, Hall, J., Wedepohl, K.H. (Eds.), The Nature of the Lower Continental Crust, London Geol. Soc., Spec. Publ., vol. 24. London Geological Society, pp. 63–70.

Cotte, N., Pedersen, H., Campillo, M., Mars, J., Ni, J.F., Kind, R., Sandvol, E., Zhao, W., 1999. Determination of the crustal structure in southern Tibet by dispersion and amplitude analysis of Rayleigh waves. Geophys. J. Int. 138, 809–819.

Cohen, J.K., Stockwell, Jr. J.W., 1997. CWP/SU: Seismic Unix Release 30: a free package for seismic research and processing. Center for Wave Phenomena, Colorado School of Mines.

Dewey, J.F., Bird, J.M., 1970. Mountain belts and the new global tectonics. J. Geophys. Res. 75, 2625–2647.

Dewey, J.F., Burke, K.C.A., 1973. Tibetan, Variscan and Precambrian reactivation: Products of continental collision. J. Geol. 81, 683–692.

Dürr, S.B., 1993. The mid- to early Late Cretaceous Xigaze forearc basin (south Tibet) sedimentary evolution and provenance of clastic sediments. Tübinger Geowissenschaftliche Arbeiten, Reihe A 15.

England, P., Houseman, G., 1986. Finite strain calculations of continental deformation, 2. Comparison with the India–Asia collision zone. J. Geophys. Res. 91, 3664–3676.

England, P., Houseman, G., 1989. Extension during continental convergence, with application to the Tibetan plateau. J. Geophys. Res. 94, 17561–17579.

Fountain, D.M., Boundy, T.M., Austrheim, H., Rey, P., 1994. Eclogite — facies shear zones — deep crustal reflectors? Tectonophysics 232, 411–424.

Fountain, D.M., Christensen, N.I., 1989. Composition of the continental crust and upper mantle; a review. In: Pakiser, L.C., Mooney, W.D. (Eds.), Framework of the Continental United States, vol. 172. Mem. Geol. Soc. Am., pp. 711–742.

Gongjian, W., Xuchang, X., Tingdong, L., 1990. The Yadong–Golmud geoscience transect in the Qinghai–Tibet plateau. Acta Geol. Sin. 3, 115–127.

Henry, P., Le Pichon, X., Goffe, B., 1997. Kinematic, thermal and petrological model of the Himalayas, constraints related to metamorphism within the underthrust Indian crust and topographic elevation. Tectonophysics 273, 17–30.

Hirn, A., Sapin, M., 1984. The Himalayan zone of crustal interaction: suggestions from explosion seismology. Ann. Geophys. 2, 123–130.

Husen, S., 1995. Krustenseismische Untersuchungen an der Indus Zangbo Sutur (Tibet). Unpublished Diploma thesis, University of Kiel, Germany, 119 pp.

Jiyang, W., Ruomli, L., Yunsheng, Z., 1996. Geothermics in China. Seismological Press, Beijing, China, 340 pp.

Kern, H., Richter, A., 1981. Temperature derivatives of compressional and shear waves in crustal and mantle rocks. J. Geophys. 49, 47–56.

Kern, H., 1982. Elastic-wave velocity in crustal and mantle rocks at high pressure and temperature. Phys. Earth Planet. Int. 29, 12–23.

Kern, H., Burlini, L., Ashchepkov, I.V., 1996. Fabric-related seismic anisotropy in upper-mantle xenoliths: evidence from measurements and calculations. Phys. Earth Planet. Int. 95, 195–209.

Kind, R., 1996. Evidence from earthquake data for a partially molten crustal layer in southern Tibet. Science 274, 1692–1694.

Le Pichon, X., Henry, P., Goffe, B., 1997. Uplift of Tibet: from eclogites to granulites — implications from the Andean Plateau and the Variscan Belt. Tectonophysics 273, 31–56.

Makovsky, Y., Klemperer, S.L., 1999. Measuring the seismic properties of Tibetan bright spots: Evidence for free aqueous fluids in the Tibetan middle crust. J. Geophys. Res. 104, 10795–10825.

McNamara, D.E., Owens, T.J., Walter, W.R., 1995. Observations of regional phase propagation across the Tibetan plateau. J. Geophys. Res. 100, 22 215–22 229.

McNamara, D.E., Walter, W.R., Owens, T.J., Ammon, C.J., 1997. Upper mantle velocity structure beneath the Tibetan plateau from Pn travel time tomography. J. Geophys. Res. 102, 493–505.

Meissner, R., Strehlau, J., 1982. Limits of stresses in the continental crust and their relation to depth-frequency distribution of shallow earthquakes. Tectonics 1, 73–89.

Meissner, R., Mooney, W., 1998. Weakness of the lower continental crust: a condition for delamination, uplift, and escape. Tectonophysics 296, 47–60.

Mengel, K., Kern, H., 1992. Evolution of the petrological and seismic Moho — implications for the continental crust–mantle boundary. Terra Nova 4, 109–116.

Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. Science 189, 419–426.

Nelson, K.D., et al., 1996. Partially molten middle crust beneath southern Tibet: synthesis of project INDEPTH results. Science 274, 1684–1688.

Parsons, B., Sclater, J.G., 1977. An analysis of the thermal structure of the plates. J. Geophys. Res. 82, 803–827.

Pfiffner, O.A., 1991. Crustal shortening in the Alps along the EGT profile. In: Freeman, Mueller, St. (eds.), Sixth EGT workshop, Strasbourg, France, pp. 255–262.

Ratschbacher, L., 1996. Kinematics of Tibet. Z. Dt. Geol. Ges. 147, 427–434.

Rodgers, A.J., Schwartz, S.Y., 1997. Low crustal velocities and mantle lithospheric variations in southern Tibet from regional Pnl waveforms. Geophys. Res. Lett. 24, 9–12.

Sapin, M., Hirn, A., 1997. Seismic structure and evidence for eclogitization during the Himalayan convergence. Tectonophysics 273, 17–30.

Tapponnier, P., 1990. The Ailao Shan–Red River metamorphic belt: Tertiary left-lateral shear between Indochina and South China. Nature 343, 431–437.

Tapponnier, P., 1981. The Tibetan side of the India–Eurasia collision. Nature 294, 405–410.

Wang, C., Shi, Y., Zhou, W., 1982. On the tectonics of the Himalaya and the Tibet plateau. J. Geophys. Res. 87, 2949–2957.

Wernicke, B., 1990. The fluid crustal layer and its implication for continental dynamics. In: Salisbury, M.H., Fountain, D.M. (Eds.), Exposed Cross-sections of the Continental Crust, Kluwer, Netherlands, pp. 509–544.

Westaway, R., 1995. Crustal volume balance during the India-Eurasia collision and altitude of the Tibetan plateau: a working hypothesis. J. Geophys. Res. 100, 15 173–15 192.

Xiao, X., Li, T., 1996. Tectonic evolution and uplift of the Qinghai–Tibet Plateau. Episodes 18, 31–35.

Yaolin, S., Yuanqing, Z., 1993. Some thermotectonic aspects of the Tibetan plateau. Tectonophysics 219, 223–233.

Yuan, X., Ni, J., Kind, R., Sandvol, E., Mechie, J., 1997. Lithospheric and upper mantle structure of southern Tibet from a seismological passive source experiment. J. Geophys. Res. 102, 27 491–27 500.

Zelt, C.A., Forsyth, D.A., 1994. Modelling wide-angle seismic data for crustal structure: Southeastern Greenville Province. J. Geophys. Res. 99, 11 687–11 704.

Zelt, C.A., Smith, R.B., 1992. Seismic traveltime inversion for 2-D crustal velocity structure. Geophys. J. Int. 108, 16–34.

Zhao, W., et al., 1997. Seismic mapping of crustal structures beneath the Indus–Yarlung suture, Tibet. Terra Nova 9, 42–46.

INDEPTH Project team, Zhao, W., Nelson, K.D., 1993. Deep seismic reflection evidence for continental underthrusting beneath southern Tibet. Nature 366, 557–559.

Zhao, W.L., Morgan, W.J., 1985. Uplift of Tibetan plateau. Tectonics 4, 359–369.

Zhao, W.L., Morgan, W.J., 1987. Injection of Indian crust into Tibetan lower crust: a two-dimensional finite element model study. Tectonics 6, 489–504.