Southern Tibet: its deep seismic structure and some tectonic implications

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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, GEODEPTH (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 \( P_M P \), 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; Tapponnier et al., 1981; Wang et al., 1982; Zhao et al., 1993, 1997). The 3500 × 1500 km² 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; Him 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...
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 Pn — and
high Sn — 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
(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 compa-
rible 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 plausi-
ble, 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 GEDEPHT 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–Nuijiang 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 Pp arrivals for the first 60 km offset of our velocity model of Fig. 3), respectively. The midpoint locations of the wide-
gle data are outlined between the GEDEPHT 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 GEDDEPTH program (German Depth Profiling of Tibet and the Himalaya) (Kind, 1996; Yuan et al., 1997). Our studies in this paper concentrate on the signals recorded by GEDDEPTH’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 (Beghouli 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.

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 \( V'_P < 6.3 \text{ km/s} \) 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 eclogite metamorphic facies takes place under appropriate conditions (Mengel and Kern, 1992; Fountain...
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 $V_p$-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 $V_p$-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; Jiayang 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 modeling.

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°C (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
Tibet is high mantle $P_v$-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
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.

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 Tibetan 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 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 seismsics 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–Nuijiang 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 Sn-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 Şengör, 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 subcrustal 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.

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