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Lesser Himalayas to Qang Tang: A 500 Km Teleseismic Deployment to Test Geodynamic Models

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ABSTRACT

The deep structure across Himalayas-Tibet is resolved along a dense seismic array by the variation of arrival times, amplitudes, waveforms and polarizations of teleseismic body waves. The Himalayas rise over a strong increase in crustal thickness. Behind, although Tibet has the same elevation, the structure and physical state vary strongly in the Lhasa block. This is further North than continental subduction would have accumulated a cold root and further South than homogenous thickening would have resulted in wholesale delamination. Evidence for flow at depth in this system does not simply mirror the tectonic features of the brittle surface. Heterogeneity along, as well as across strike and with depth demands models other than steady-state two dimensional approximations in plane or section. Further data collecting experiments will be needed.

INTRODUCTION

Continental convergence between India and Siberia has been accommodated in Tibet - Himalayas by variations in thickness of the crust and subcrustal lithosphere, or lateral transport. A wide range of models of evolution is allowed since only loose constraints on deep structure have been given by geophysical observations at distance. Instead, we deployed there a linear array of temporary seismographs to record teleseismic body waves in an attempt to extend in depth our early crustal reconnaissance (Hirn et al., 1984, a, b). A high resolution of structures is then first related to a dense station spacing, which we set at 15 km. From the Lesser Himalayas of Nepal to the Qang Tang terrane of Central Tibet (Fig. 1) we deployed 60 digital instruments over 500km, 25 had 3-component broad- band sensors to also record shear waves.

Variations of P wave residuals resolve significant heterogeneity. It is larger than expected for two simply overriding crusts or lithospheres under whole Tibet (Powell and Conaghan, 1973 ; Barazangi and Ni, 1982). It is not distributed as in models which accumulate a subducting cold slab (Molnar, 1984; Mattauer, 1986), or eventually detach it (Bird, 1978; Nelson, 1992), beneath a scraped-off crustal accretionary wedge. Variations in S residuals and in the attenuation reveal a change of physical state in the crust-mantle system far south of that considered in models of wholesale delamination of homogeneously thickened lithosphere (England and Houseman, 1989).

Shear-wave splitting orientation ignores major surface features like the active right-lateral shear zone central to models of continental escape or rigid lithospheric blocks rotation (Armijo et al., 1989). Its magnitude relates with slow and attenuating upper lithosphere and its orientation may then indicate ductile flow in layers of partial melt which spread out the thickening or collapse of the plateau.

VARIATIONS OF CRUST AND LITHOSPHERE THICKNESS : P RESIDUALS

As in an early teleseismic test through the Pyrenees (Hirn et al., 1984d) an abrupt change in arrivals of steep incidence P waves can be seen through the

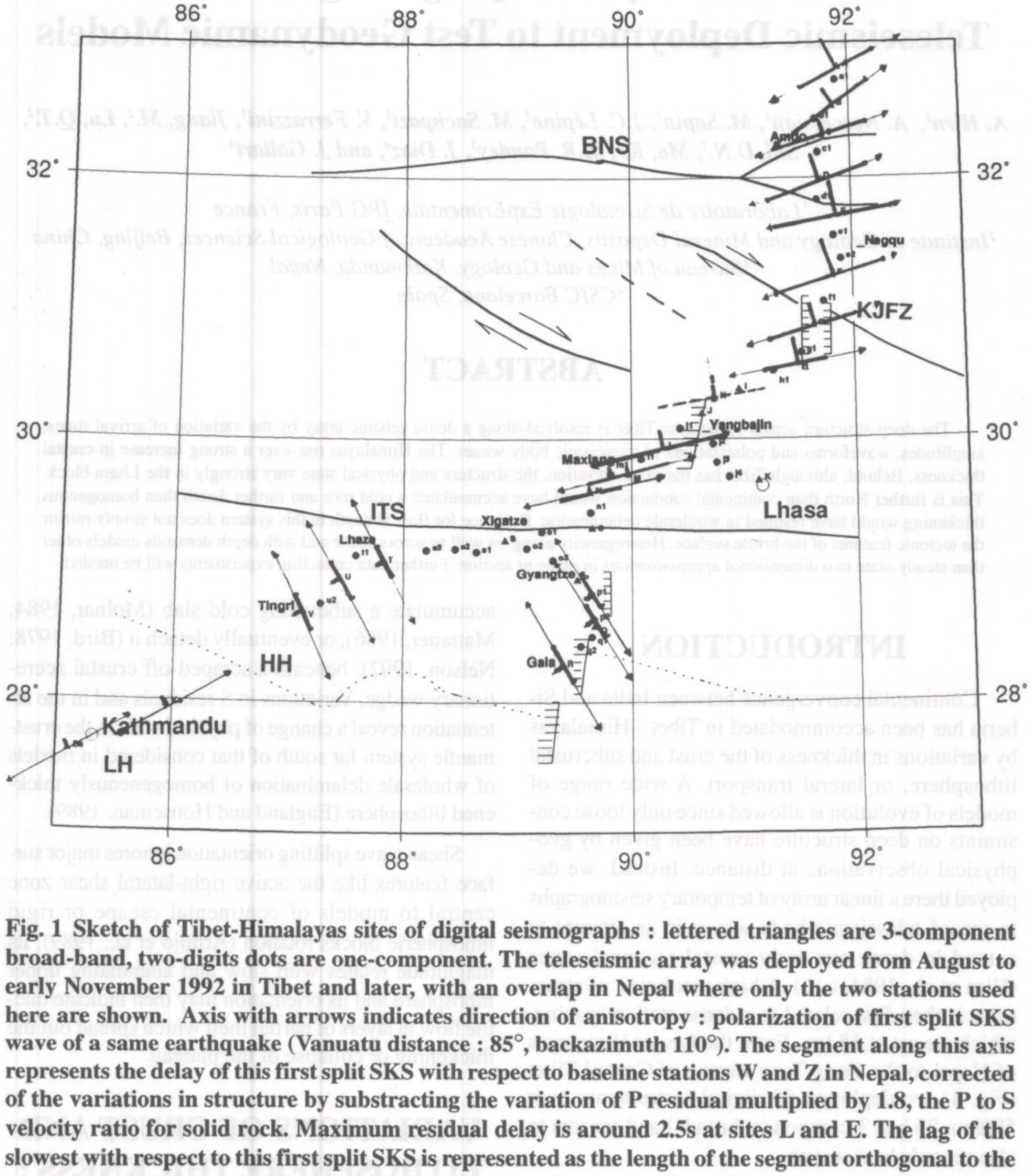


Fig. 1 Sketch of Tibet-Himalayas sites of digital seismographs : lettered triangles are 3-component broad-band, two-digits dots are one-component. The teleseismic array was deployed from August to early November 1992 in Tibet and later, with an overlap in Nepal where only the two stations used here are shown. Axis with arrows indicates direction of anisotropy : polarization of first split SKS wave of a same earthquake (Vanuatu distance : 85°, backazimuth 110°). The segment along this axis represents the delay of this first split SKS with respect to baseline stations W and Z in Nepal, corrected of the variations in structure by substracting the variation of P residual multiplied by 1.8, the P to S velocity ratio for solid rock. Maximum residual delay is around 2.5s at sites L and E. The lag of the slowest with respect to this first split SKS is represented as the length of the segment orthogonal to the arrow. Selected geological features are sketched along the array : Jurassic suture zones of Banggong-Nujiang (BNS) between the Qang Tang and the Lhasa block and Cretaceous suture of the Indus-Tsangpo rivers (ITS). Higher Himalayas (HH) and the Kangmar-Lhagoi Khangri granite-gneiss belt of Tibetan Himalayas between HH and ITS Karakorum Jiali (KJFZ) quaternary shear zone of right-lateral escape of Central Tibet. North south faults limiting graben of quaternary extension.

High Himalayas (Fig. 2). It can be attributed to a rather abrupt change in Moho depth beneath it. This is consistent with our controversial suggestion (Lépine et al., 1984 ; Molnar, 1988 ; Hirn, 1988) from sparse wide angle reflection seismics, as was the case in the Pyrenees where multichannel vertical reflection came to comfort it. The extension of the 70 km-deep Moho South towards the High Himalayas in spite of the upslope of the Bouguer anomaly (Wu et al., 1991) has been confirmed by reflection seismics (Nelson et al., 1992). This method will have to reach further South to test for abrupt topography now suggested in addition by teleseismic residuals. From the Indian plate in Nepal to the ITS, Indus Tsangpo Suture, there is then hardly a relative residual left for the mantle. This provides no evidence, as has not been found either by Pandey et al. (1991), in favour of models with an important slab of fast lithospheric mantle under the Tibetan Himalayas. Neither if it were only detached from the stacked crust and accumulated as a fast body beneath (Molnar, 1988) nor if it were delaminated and replaced by slow asthenosphere up to the crust (Bird, 1978 ; Nelson, 1992).

From its constant elevation, common sense would infer tabular structure through whole Tibet-Himalaya. However residuals of PKP waves with steep incidence from the antipodes range over one second (Fig. 3a). This is as large as reported across the East-African rift (Green and Meyer, 1992). Earlier residuals in the North would be consistent with the shallower position on average of the Moho suggested from wide angle reflection (Hirn et al., 1984b) although the section being 100 km westward should not be compared in detail. Such a variation in crustal thickness without clear inverse correlation with Bouguer anomaly implies further heterogeneity within crust and mantle. These can be estimated from the variation of residuals with azimuth and incidence. Late residuals are largest for the center part of the line when waves come along it, from ENE and NE (Fig. 3b,c). They are largest for the northern half of it when waves arrive orthogonal to the line, from WNW (Fig. 3d) or ESE (Fig. 3g). This is the contrary of PKP ; here a longer path in a slow mantle in the North overprinted the shorter time at vertical incidence as expected if this was related to thinner crust. On propagation from NE along the profile, waves may accumulate delays in the slow mantle part from North and hence reach largest residual in the middle.The effect of the slow mantle can be enhanced, and is seen as several seconds of delay in the North, for paths of nearer sources chosen to give grazing incidence at that depth (Fig. 3e).

Sharper lateral variations are probably intralithospheric. An auxiliary line of stations was emplaced across the strong 70 mgal decrease of the Bouguer anomaly (Wu et al., 1991) from Lhasa to WNW. It finds a correlation with residuals which systematically increase very steeply from station K towards J and L, M on the main line (Fig. 3a,b,c). Contrast is here along, as well as across the recognized E-W structural trends. South of ITS the Gyangze-Gala graben easy access is used by our mainline and other surveys (Hirn et al., 1984 a, c ; Nelson et al., 1992). It may not be representative of Himalayan structure since it is the major quaternary graben along which the very negative Bouguer anomaly extends southwards. We tested this with an auxiliary traverse of the Tibetan Himalayas 150km further West : the Gyangze-Gala mainline appears late by up to 0.4 s for vertical PKP (Fig. 3a). The extreme difference of over 1s between the two lines in Fig 3c we attribute to delay accumulated on propagation from NE, along the main line and low Bouguer anomaly towards Gala, whereas rays to 150 km further West propagate across a more representative Bouguer anomaly parallel to Himalayan strike. The geometry and magnitude of the velocity anomaly detected will be constrained further by tomographic inversion.

VARIATIONS OF PHYSICAL STATE : S RESIDUALS AND ATTENUATION

Teleseismic array experiments had yet to be shown to return results for shear waves, the recording of which adds methodological, technical and logistical difficulties. Reported lack of Sn transmission (Ni and Barazangi, 1983) as well as a regional low velocity anomaly in the mantle or the crust from surface wave dispersion (Brandon and Romanowicz, 1986; Bourjot and Romanowicz, 1992) have been associated to Central Qang Tang. Our line however

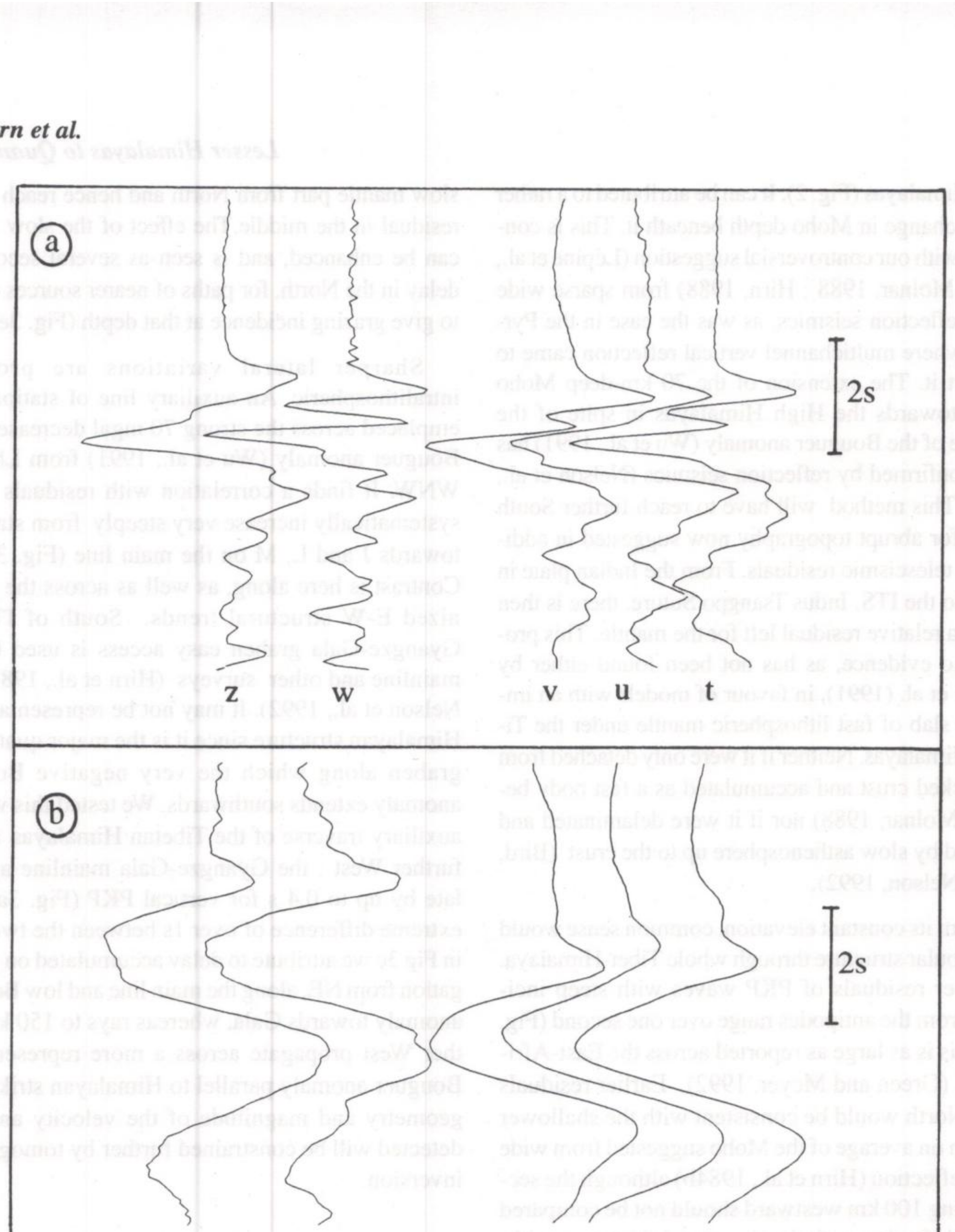


Fig. 2 Vertical component seismograms of P waves on a 250 km section through the High Himalayas Differential times are corrected for propagation in a standard Earth and elevation. From the right, Tibetan Himalayas, stations T, U,V in the North, to the South of the High Himalayas, station W and the Lesser Himalayas, station Z.

a) Waves from Andreanof (distance 67°, backazimuth 43°) propagate from NE. They show no difference in residual arrival time along the line of stations. The first arriving rays at the Nepalese stations are still those refracted or diffracted on the deep Tibetan-Moho reaching far South.

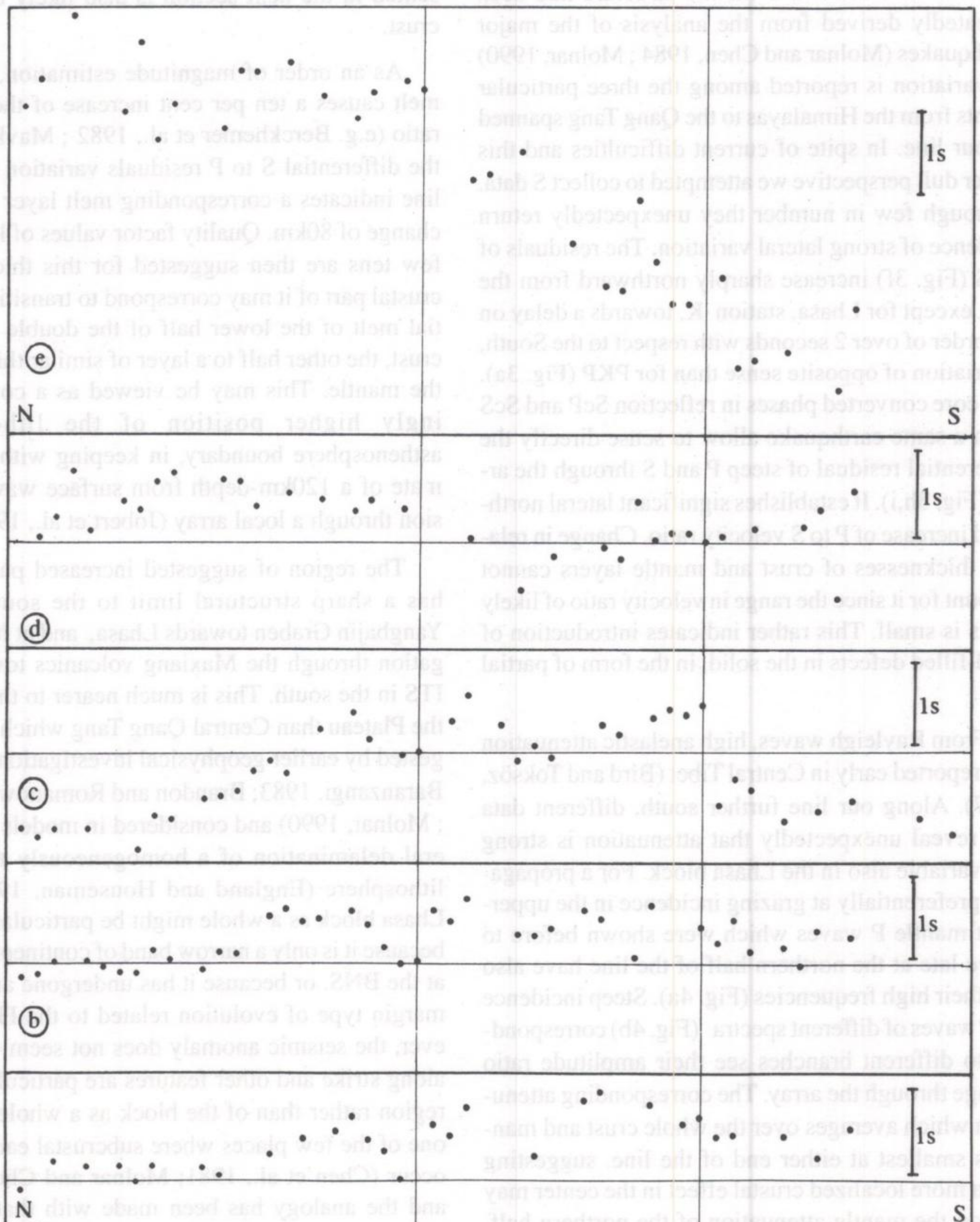
b) Waves from Chile (distance : 169°, backazimuth : 270°), quasi vertical PKP illustrate extreme delay of 1s between T, U and V which are on 70km thick crust on one side and Z and even W which are thus shown to be still on thinner, Indian crust which reaches far North.

ended at the southern edge of this terrane. Also, whereas variations in S mantle structure had been repeatedly derived from the analysis of the major earthquakes (Molnar and Chen, 1984 ; Molnar, 1990) no variation is reported among the three particular events from the Himalayas to the Qang Tang spanned by our line. In spite of current difficulties and this rather dull perspective we attempted to collect S data. Although few in number they unexpectedly return evidence of strong lateral variation. The residuals of SKS (Fig. 3f) increase sharply northward from the ITS, except for Lhasa, station K, towards a delay on the order of over 2 seconds with respect to the South, a variation of opposite sense than for PKP (Fig. 3a). The core converted phases in reflection ScP and ScS from a same earthquake allow to sense directly the differential residual of steep P and S through the array (Fig. 3h,i). It establishes significant lateral northward increase of P to S velocity ratio. Change in relative thicknesses of crust and mantle layers cannot account for it since the range in velocity ratio of likely rocks is small. This rather indicates introduction of fluid-filled defects in the solid, in the form of partial melt.

From Rayleigh waves, high anelastic attenuation was reported early in Central Tibet (Bird and Toksöz, 1977). Along our line further south, different data sets reveal unexpectedly that attenuation is strong and variable also in the Lhasa block. For a propagation preferentially at grazing incidence in the uppermost mantle P waves which were shown before to arrive late at the northern half of the line have also lost their high frequencies (Fig. 4a). Steep incidence PKP waves of different spectra (Fig. 4b) corresponding to different branches see their amplitude ratio change through the array. The corresponding attenuation which averages over the whole crust and mantle is smallest at either end of the line, suggesting that a more localized crustal effect in the center may add on the mantle attenuation of the northern half. The attenuation factor changes by several tenths of a second, a same order of magnitude as from the Rayleigh wave estimate. For the crust itself, we suggested significant attenuation in its lower half as one way to account for the spectral ratio of explosion-generated P waves (Hirn and Sapin, 1984) ; it would be larger in the North of the Lhasa block than South of the ITS. Attenuation of the late split SKS, presented in the next section is also likely due to the crust.

As an order of magnitude estimation, if partial melt causes a ten per cent increase of the velocity ratio (e.g. Berckhemer et al., 1982 ; Mavko, 1980), the differential S to P residuals variation along the line indicates a corresponding melt layer thickness change of 80km. Quality factor values of less than a few tens are then suggested for this thickness. A crustal part of it may correspond to transition to partial melt of the lower half of the double thickness crust, the other half to a layer of similar thickness in the mantle. This may be viewed as a correspondingly higher position of the lithosphere-asthenosphere boundary, in keeping with our estimate of a 120km-depth from surface wave dispersion through a local array (Jobert et al., 1985).

The region of suggested increased partial melt has a sharp structural limit to the south of the Yangbajin Graben towards Lhasa, and at its prolongation through the Maxiang volcanics towards the ITS in the south. This is much nearer to the edge of the Plateau than Central Qang Tang which was suggested by earlier geophysical investigations (Ni and Baranzangi, 1983; Brandon and Romanowicz, 1984 ; Molnar, 1990) and considered in models of a general delamination of a homogeneously thickened lithosphere (England and Houseman, 1989). The Lhasa block as a whole might be particular at depth because it is only a narrow band of continent accreted at the BNS, or because it has undergone an Andean margin type of evolution related to the ITS. However, the seismic anomaly does not seem to extend along strike and other features are particular of this region rather than of the block as a whole. Tibet is one of the few places where subcrustal earthquakes occur (Chen et al., 1981; Molnar and Chen, 1983) and the analogy has been made with that beneath Kilauea where the high strain rate necessary to produce deep earthquakes is related to mantle magma flow. The two deep earthquakes recognized in whole Tibet occurred in the Lhasa block right at the limit of the lithospheric anomaly south of Maxiang. The most recent Tibetan volcanism, apart from the basalts of Northern Qang Tang is right here : Maxiang suite



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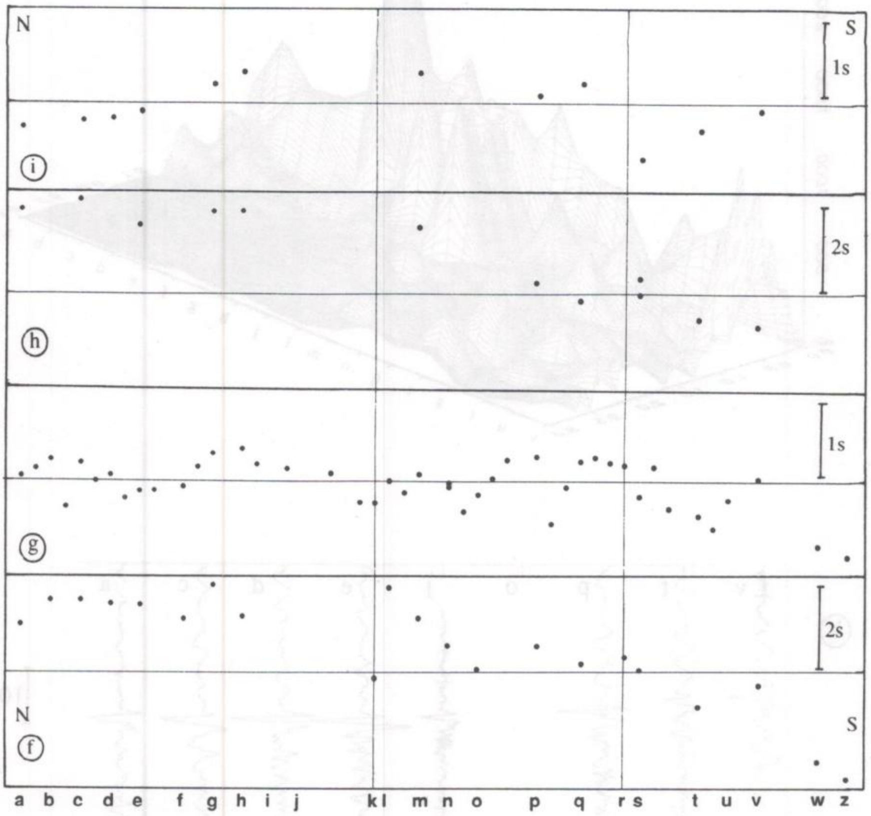

Fig. 3 Relative P or S travel time residuals obtained by waveform matching through the array, corrected to the 3.6 km elevation of station K at Lhasa. Note that K and the 3 stations to the left of it are off the main line and that also the last stations to the right, S to V, form a second transect of the Tibetan Himalayas 150km west of O to R along the main section.a) PKP waves, Chile, distance D = 163°, backazimuth B = 260°Earlier residuals in the northern part. Decrease of residuals off the main line to K, Lhasa. In the South, the Western traverse is earlier than the main line b) P waves, Honshu, D = 41°, B= 77°. Overall features similar as for a) c) P waves Andreanof, D = 68°, B = 43°. Propagation is from NE, along the main line.Waves acquire a relative residual twice that before on propagating beneath the northern, to the central part of the line. This persists south of ITS and to the end of the main line at Gala (R). On the western traverse of the Tibetan Himalayas residuals are as much as 1s earlier. d) P waves, Romania, D = 51°, B = 305°. Propagation is fan-like broadside to the main line. At variance with previous azimuths, the whole northern half now has the largest residuals. The relative delay between the two lines south of ITS is reduced, rays come from broadside. e) P waves, Tadjikistan, D = 16°, B = 310°. Propagation direction like for d), but with grazing incidence of rays in the uppermost mantle enhancing its effect. With respect to the South residuals are delayed but here by up to 3 s to f) SKS waves, Vanuatu, D = 84°, B = 110°. Relative residuals are scaled by 1.8 to be compared with those for P. The S relative residuals incrase sharply northwards of the ITS by 1.5 s (except point K, Lhasa), whereas for P they remain flat for the same event g) or decrease for a same steep incidence, like the PKP of a). Strong departure of sealed behaviour not accounted by any variation of distribution of solid rocks all of which have velocity ratio close to 1.8, but is evidence for melt portion in solid. g) P waves of event f) for comparison, although incidence is here less steep. h) and i) ScS and ScP waves, Kuriles (D = 67°, B = 43°). The two core reflections provide similar steep incidence form a same earthquake. Scaled relative residuals of h) with wave arriving as S much later in the North than for i) with wave arriving as P.

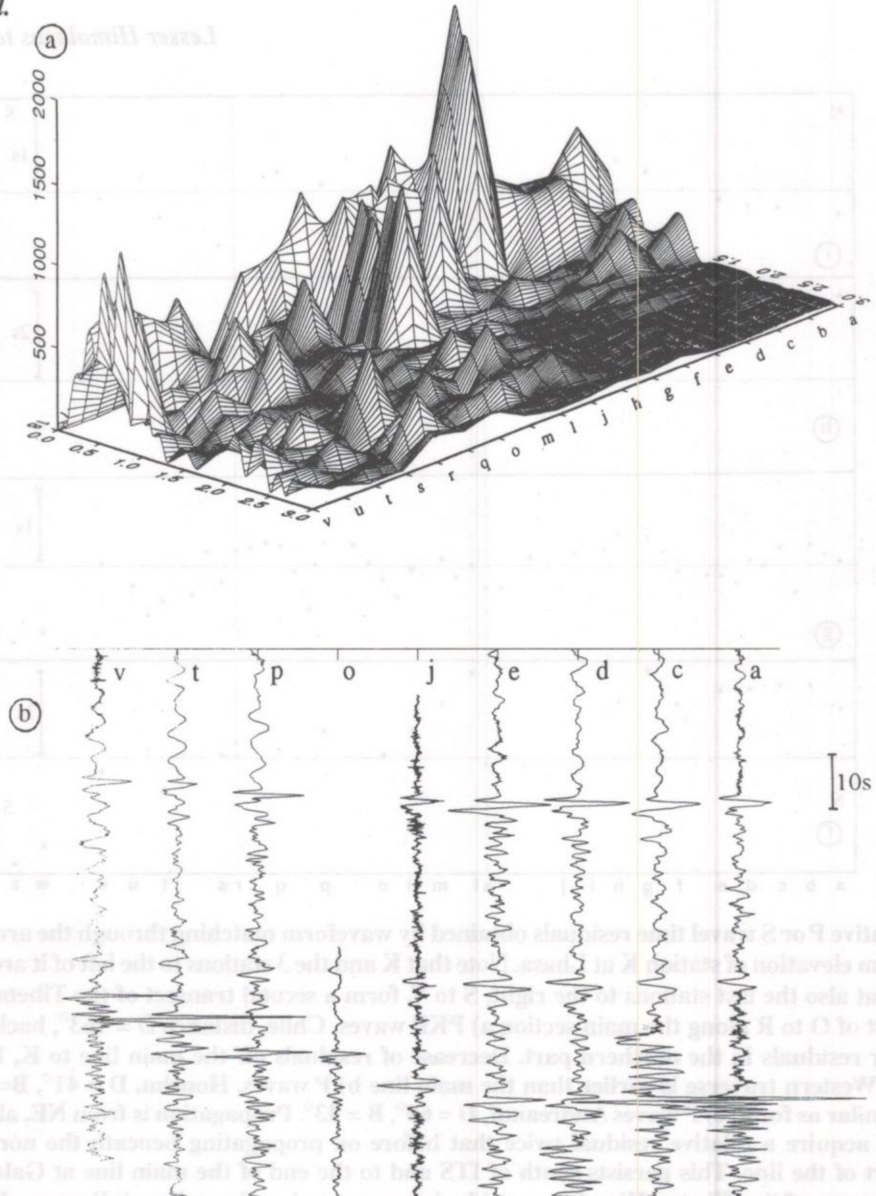

Fig. 4 a) Display of amplitude spectra between 0 and 3 Hz of initial 10s of P waves from an earthquake in Tadjikistan arriving fan-like on the array. Note the absence of amplitude above 1.5 Hz in the northern half with respect to the southern. b) Waves PKIKP and PKP2 from Chile-Argentina deep earthquake with dominant signal of different periods of 3s and 1s respectively. Significant decrease of amplitude of the last, higher frequency one in the central part of the line with respect to the extremities of the line indicating lateral change in average crust-mantle attenuation. A change of amplitude ratio between the two waves by a factor of 5 to 10 corresponds to a variation in attenuation factor t*, which is propagation time in the attenuating layer divided by its quality factor, on the order of 0.7 to 1s. This is of the same order as the equivalent attenuating layer thickness of 2 km from Rayleigh waves[15]. For an 80km thickness, Q would be then on the order of 10 to 20.

Northern Qang Tang is right here : Maxiang suite of potassic calcalkaline volcanism as recent as 12 Ma postdating collision and orogeny (Coulon et al., 1986) and taken as example of result of lithospheric delamination (Turner et al., 1992). This coincidence of deep structural, seismic and density anomaly, present seismic activity, youth and type of volcanism suggests a situation at the edge of a mantle upflow which may not extend over all Tibet along strike.

FLOW DIRECTIONS : SHEAR WAVE SPLITTING

We have observed SKS splitting (Vinnik et al., 1989 ; Silver & Chan, 1991) at 20 sites on a profile from Central Tibet to Nepal. We used Lennartz Electronics built L3D/5s sensors, broadened by a decade to low frequency from Mark Products L22 geophones of 0.5 s period. Instead of high-cut frequency filtering at 8 s period necessary to process the data of analog recorders (Makeyeva et al., 1992), or at the Nyquist frequency of reported digital sampling at low rate of 5 or 8 Hz (Vinnik et al., 1989), we may hence process the very details of waveforms with precise time resolution. Orthogonal projection of seismograms with azimuth separates the two split waves and evidences a slight difference between their waveforms (Fig. 5). Accounting for this observation by allowing for anisotropy in attenuation leads to retrieve from the analysis a same orientation of N 70∞E within 10∞ for the fast axes at the 8 northern stations, rather than a gradual rotation of the fast orientation reported over fewer stations (Mc Namara et al. 1992). Strong changes occur abruptly further South between large regionas of constant orientation.

In models of the convergence which consider subduction of the subcrustal lithosphere, by shear of the crust in mantle overdrive (Molnar, 1992), anisotropy would be predicted with a northward orientation, or in case of upwelling under the mountain chain itself along its strike (Makeyeva et al., 1989). In models with lithosphere thickening by homogeneous deformation (Dewey & Burke, 1973) anisotropy would strike orthogonal to compression. If wholesale delamination then occurred the frozen-in anisotropy should melt- or fall-off. If we go to map view another class of models of lithospheric evolution is dominated by lateral extrusion through localized finite strain along faults (Armijo et al., 1989). If regarded as deep reaching they may induce anisotropy in their ESE direction. They are proposed to limit a few rigid plates which move with respect to each other and to the asthenosphere, the corresponding displacement field being oriented slightly East of North (Avouac & Tapponnier, 1992). The orientations of anisotropy we observe do not fit any of prediction but the last approximately.

Anisotropy sampled by SKS is attributed to preferred orientation of olivine in the mantle, in which the early wave is fast with respect to the isotropic case (Silver & Chan, 1991 ; Vinnik et al., 1992). Along our dense Tibetan line we remark that the large delays between split waves occur instead where the residual is latest and attenuation largest, in the northern half (Fig.1). Hence our split waves are both slow waves. Velocity anisotropy is then likely caused by defects in the solid matrix (Crampin, 1991), the filling fluid being here partial melt and attenuation anisotropy is expected. A contribution of the crust to SKS splitting has been discarded as general on the basis of absence of evidence of splitting of the wave converted from P to S upon refraction through the Moho. For Tibet there is a suggestion to the contrary (Fig. 6). Hence a large part of the anisotropy of SKS may be due to ductile orientation of partial melt shallow under the station, even within the crust.

The 200 km northern segment, with 8 stations having constant N70∞E orientation and with delays between split waves up to a second crosses the E-W Banggong-Nujiang Suture (BNS) of Jurassic age and also the N120∞E Karakorum Jiali Fault Zone (KJFZ), the major quaternary and present seismically active dextral fault zone. That the direction of anisotropy would keep constant and have that orientation was certainly not predictable from geological models which give a major signification to the KJFZ (Armijo et al., 1989) nor from models opposing a hot deep structure of the Qang Tang to that of the Lhasa block across the BNS.

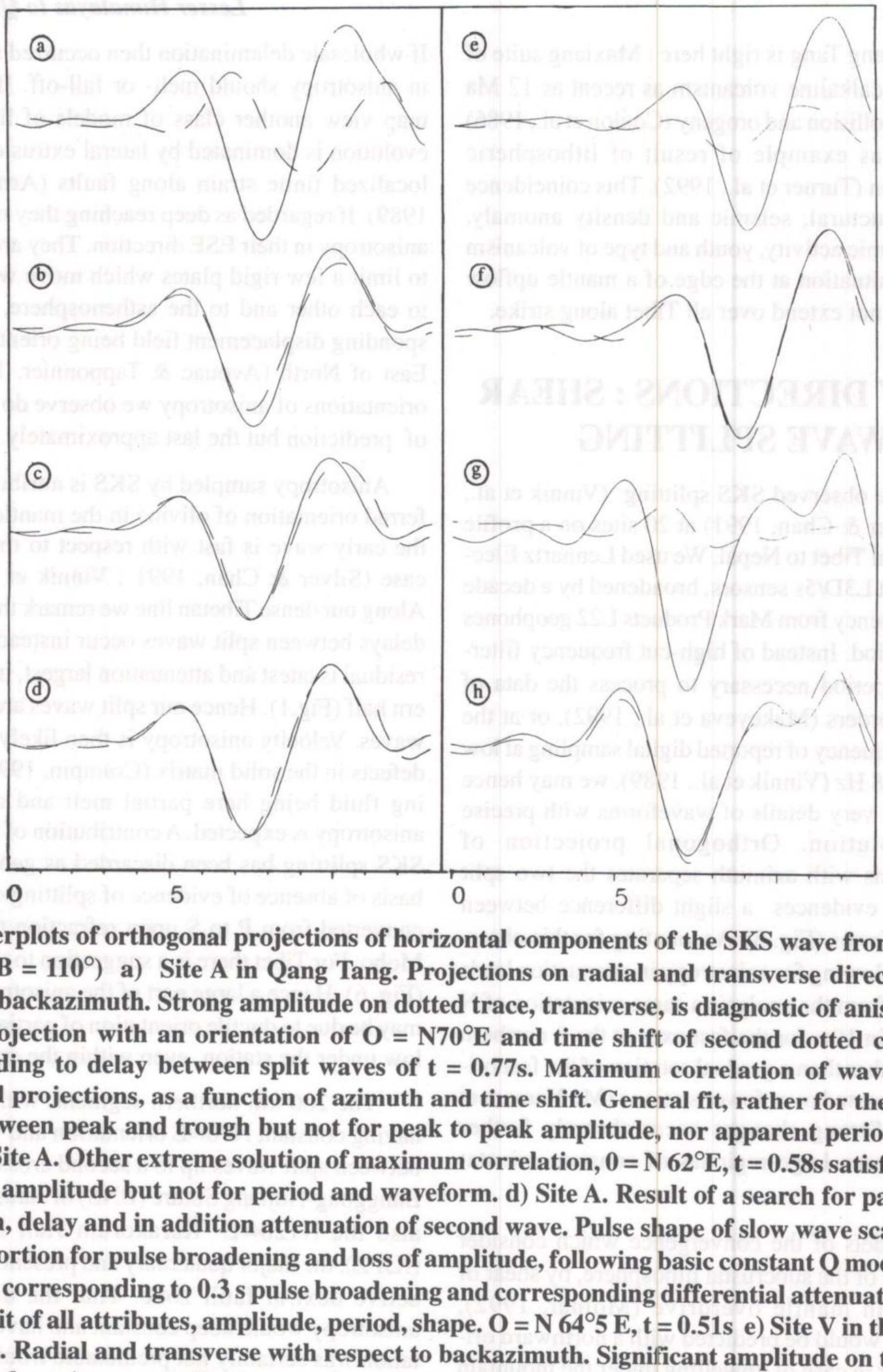

Fig. 5 Overplots of orthogonal projections of horizontal components of the SKS wave from Vanuatu (D = 85°, B = 110°) a) Site A in Qang Tang. Projections on radial and transverse directions with respect to backazimuth. Strong amplitude on dotted trace, transverse, is diagnostic of anisotropy. b) Site A. Projection with an orientation of O = N70°E and time shift of second dotted component corresponding to delay between split waves of t = 0.77s. Maximum correlation of waveforms on orthogonal projections, as a function of azimuth and time shift. General fit, rather for the apparent period between peak and trough but not for peak to peak amplitude, nor apparent period between peaks. c) Site A. Other extreme solution of maximum correlation, 0 = N 62°E, t = 0.58s satisfactory for maximum amplitude but not for period and waveform. d) Site A. Result of a search for parameters, orientation, delay and in addition attenuation of second wave. Pulse shape of slow wave scaled in the same proportion for pulse broadening and loss of amplitude, following basic constant Q model[37]. Seale factor 6 % corresponding to 0.3 s pulse broadening and corresponding differential attenuation factor. Excellent fit of all attributes, amplitude, period, shape. O = N 64°5 E, t = 0.51s e) Site V in the Tibetan Himalayas. Radial and transverse with respect to backazimuth. Significant amplitude on transverse with time of maximum amplitude near time of zero amplitude on radial, diagnostic of anisotropy. f) Site V. Maximum of correlation between wave shapes here for a fast direction West of North. O = N30°W, t = 0.26s g) Site W in Nepal. Radial and transverse. Small amplitude on transverse but characteristic of anisotropy h) Site W in Nepal. Maximum correlation between wave shapes for a fast direction O = N60°E, t = 0.26 s

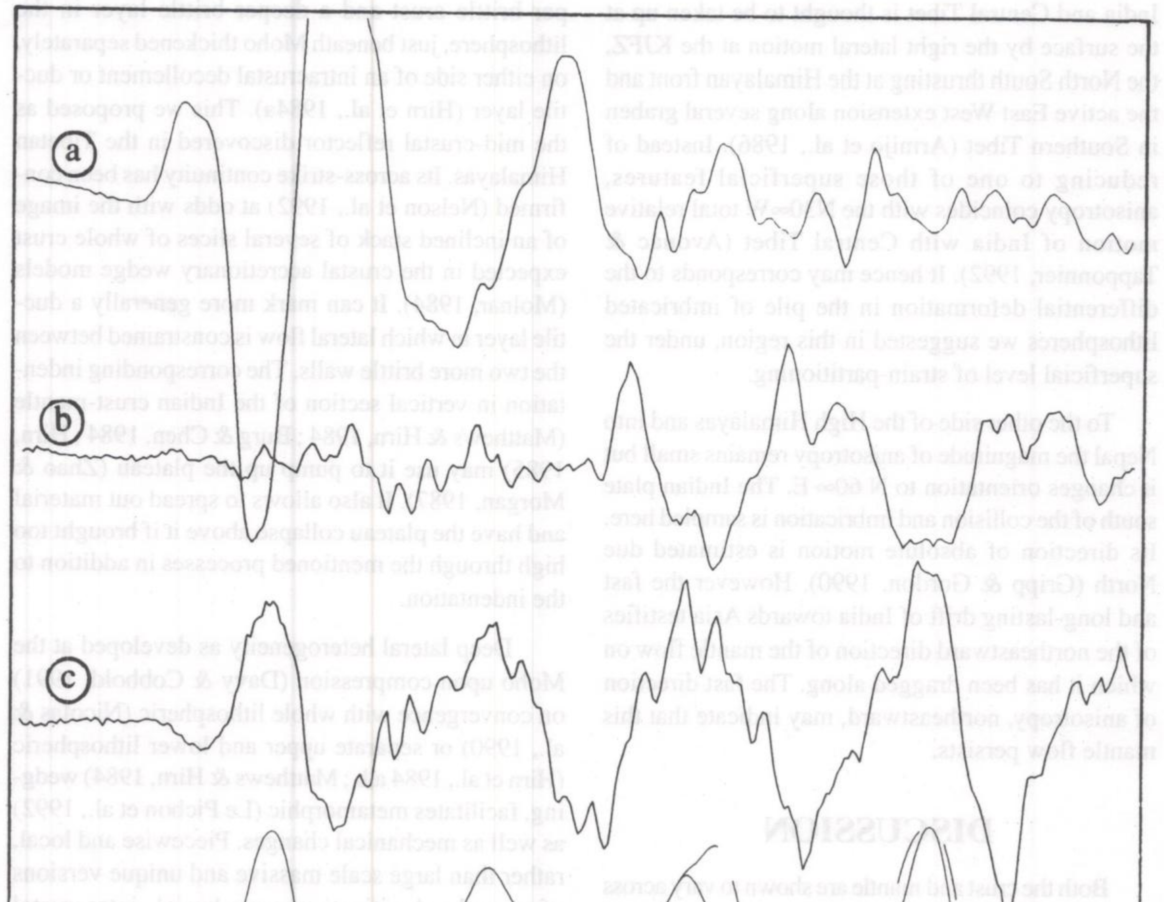

Fig. 6 Site G, P waves, New Guinea, D = 63°, B = 113° depth : 215 km First arrival P on a) vertical component and c) E-W component almost radial. Significant arrival 7s after on b) N-S component, almost transverse, diagnostic of split shear wave on conversion at deep Moho under the station. Overplots in N70°E azimuth in d). The second, dotted is seen to lag behing at its onset, around time mark 9, about 0.6s, consistently with SKS analysis.

South of ITS, in the Tibetan Himalayas, anisotropy is clear at the 6 sites. It has a N30∞ W orientation and a small magnitude. Motion between India and Central Tibet is thought to be taken up at the surface by the right lateral motion at the KJFZ, the North South thrusting at the Himalayan front and the active East West extension along several graben in Southern Tibet (Armijo et al., 1986). Instead of reducing to one of those superficial features, anisotropy coincides with the N30∞W total relative motion of India with Central Tibet (Avouac & Tapponnier, 1992). It hence may corresponds to the differential deformation in the pile of imbricated lithospheres we suggested in this region, under the superficial level of strain-partitioning.

To the other side of the High Himalayas and into Nepal the magnitude of anisotropy remains small but it changes orientation to N 60∞ E. The Indian plate south of the collision and imbrication is sampled here. Its direction of absolute motion is estimated due North (Gripp & Gordon, 1990). However the fast and long-lasting drift of India towards Asia testifies of the northeastward direction of the mantle flow on which it has been dragged along. The fast direction of anisotropy, northeastward, may indicate that this mantle flow persists.

DISCUSSION

Both the crust and mantle are shown to vary across Tibet, indicating processes in addition to a mere wholesale crustal superposition (Ni & Barazangi, 1982). Partial melt regions are indicated from lateral variation of seismic velocity and attenuation, they flow as indicated by seismic anisotropy, under and across the superficial tectonic features along which pieces of brittle upper crust adjust their differential motions not simply related to this present direction. The ductile flow can be coupled to the general asthenospheric and plate motion and also to strain within the crust thought to result from topographical surelevation (Bird, 1991). Elevation can have been enhanced from that resulting of mere crustal thickening by a subsequent lithospheric delamination (England & Houseman, 1989) or density changes due to metamorphism (Le Pichon et al., 1992).

To account for complex images from wide angle reflection seismics, we suggested a variant of homogenous lithospheric thickening in which the upper brittle crust and a deeper brittle layer in the lithosphere, just beneath Moho thickened separately, on either side of an intracrustal decollement or ductile layer (Hirn et al., 1984a). This we proposed as the mid-crustal reflector discovered in the Tibetan Himalayas. Its across-strike continuity has been confirmed (Nelson et al., 1992) at odds with the image of an inclined stack of several slices of whole crust expected in the crustal accretionary wedge models (Molnar, 1984). It can mark more generally a ductile layer in which lateral flow is constrained between the two more brittle walls. The corresponding indentation in vertical section of the Indian crust-mantle (Matthews & Hirn, 1984 ; Burg & Chen, 1984 ; Hirn, 1985) may use it to pump up the plateau (Zhao & Morgan, 1987). It also allows to spread out material and have the plateau collapse above it if brought too high through the mentioned processes in addition to the indentation.

Deep lateral heterogeneity as developed at the Moho upon compression (Davy & Cobbold, 1991) on convergence with whole lithospheric (Nicolas & al., 1990) or separate upper and lower lithospheric (Hirn et al., 1984 a,b ; Matthews & Hirn, 1984) wedging, facilitates metamorphic (Le Pichon et al., 1992) as well as mechanical changes. Piecewise and local, rather than large scale massive and unique versions of crustal eclogitization upon burial, intracrustal metamorphism or melting, or lower lithosphere peeling off, sinking and replacement by asthenosphere can then be induced. They then do not need to be symmetrical with respect to the center of Tibet, nor have cylindrical symmetry mimicking accretion limits or terrane ages.

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