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Tibetan Plateau: Progress, But Many First Order Questions Remain.

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Being the largest region of high relief on the planet, the Tibetan Plateau has been a very active area of research for more than thirty years during which time major progress has been made in understanding the processes of its evolution. Nevertheless, there remain numerous first order questions concerning the processes of Tibetan crust, lithosphere and mantle evolution since the India/Eurasia collision. Major questions include: how the large magnitude of convergence since collision has been absorbed, what processes lead to the low-relief of the Tibet*an* topographic surface, why does this low-relief surface develop across many different lithospheric units, how to explain mass balance of crust during post-collisional convergence that requires decoupling within the lithosphere, and howmany different tectonic processes have been active at different times in the development of the Tibetan plateau*?*

Since the advent of plate tectonics, the underpinnings of the Tibetan Plateau have been interpreted to be the result of *a* Mesozoic and Paleozoic collage assembly of continental and oceanic fragments,which were later subjected to large-scale intracontinental shortening following the India/Eurasia collision ~50 m. y. ago. Analysis of oceanic magnetic anomalies indicates the convergence between India and Eurasia to be ~3600 km and~2700 km at the east and west Himalayansyntaxes respectively, an enormous amount that should be evident in the geology. The processes of how this shortening was absorbed were varied in time and space, but remain quantitativelycryptic.

Uncertain, but large amounts of convergence were absorbed in the Himalaya, although geological studies have generally revealedonly small amounts of shortening within the plateau to their north. Pre-collisional processes formed an elevated Andean margin, with probable thickening of crust on the southern Eurasian margin as oceanic lithosphere was subducted northward beneath it. Early Cenozoic post-collisional deformation is recorded in narrow, elongated belts of shortening within central and southern Tibet and reached into the northeastern part of the plateau where shortening and strike-slip faulting ha*ve* been more active in the late Cenozoic. Calculations of plateau elevation, with probable attendant crustal thickening, indicate Early Cenozoic high elevations (~3-4 km) in central Tibet. If so, there must have been at that time an eastern Tibetan plateau margin for which there is presently no evidence for its existence; current studies indicate *t*hat eastern Tibet was not elevated until late Miocene time. How this Early Cenozoic elevation was achieved remains unclear because surface geology shows dated amounts of shortening too small to achieve such elevation. Perhaps we must look for processes that either shorten and thicken the lithosphere without being expressed in surface geology, or that are accompaniedby removal of lithosphere during processes of intracontinental convergence. Geophysical studies of Tibetan lithosphere only yield present day data from which to interpret the pastevolution of lithospheric processes. Conclusion: Tibetan time/space relationships have proven to beextremely difficult to unravel.

Several first order features of the Tibetan plateau are important in understanding its processes of formation. The topography of the plateau, with an average elevation of near 5 km, has generally low relief, except for the rugged relief in the northeastern part of the plateau and in the area west of the Karakorum fault. The low relief of most of the plateau is developed across nearly all its major tectonic elements such that their diverserock assemblages and structures have little topographic expression. This suggests that tectonic units defined by surface geology have little influence on plateau topography and place its main controls within the deeper part of the crust and lithosphere. During the late Cenozoic stages of plateau formation, processes at lower crustal and upper mantle levels have been more uniform and by ductile deformation that smoothed surface relief by shallow isostatic compensation — not only by vertical, but also by

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horizontal flow. Original differences in the deeper crust and upper mantle have been reduced by development of more uniform ductility during post-collision evolution. Such compensation must extend beyond the southeastern margin of the plateau where the surface elevation has a broad and gentle slope to the southeastto near sea level. Similar compensation is reduced or generally lacking in the northeastern part of the plateau where deformation has been particularly active in the late Cenozoic, and west of the Karakorum fault where the shallowgeometry of the cool subducted Indian plate under that part of the plateau inhibited shallow isostatic compensation.

Following collision, assuming about one third of the ~3600 km of Indian crust is absorbed by thrusting in the Himalayathe reminder is too large by about one half to have been abosorbed in the present crustal thickness in the plateau. Several processes have been proposed to resolve the problem: subduction of lower continental crust, delamination of lower crust/lithosphere, and lateral flow (extrusion) beyond the limits of where crustal thickening occurred within the plateau. These processes require decoupling between surface geology and deeper crust and mantle, such that below the level of inferreddecoupling the rocks can have very different character from those of the upper crust and their protoliths, and theirbehavior cannot be determined from upper crustal geology. Greater resolution of geophysical techniques is required to reveal the nature of the sub-decoupling rocks.

Tectonic processes during plateau formation have different expressions in time and space as well as at both upper and deeper crustal levels. Within the Himalayan subduction system there are marked lateral changes. Beneath western Tibet recent tomography shows thatthe Indian subducted slab is nearly horizontal and underlies most of the region, whereas toward the central plateau it extends ~200-300 km beneath southern Tibet to where a steep and broken off part of the Indian slab appears to lie within the deeper mantle south of the Himalaya. But most interestingly, near the eastern syntaxis where the greatest convergence must have taken place, the Indian lithosphere underlies only a very narrow part of the external Himalaya, appeartomographcially as a large irregular mass, and does not underlie the plateau. The thickening process below the plateau must be different in these western, central, and eastern regions, and in the east it could be argued that material is being carried laterally to the southeast away from the subduction zone. GPS data shows the upper crust in southeast Tibet is moving from Tibet clockwise around the eastern syntaxis into the Indoburmansubduction zone; perhaps, lower crust and mantle is moving similarly. Such motion has probably been active for the past 15+ m.y. and is an extrusion process moving material from Tibet eastward beyond the syntaxis.The extrusion around the syntaxis is expressed at the surface and in the upper crust by major fault zones that mark velocity gradients in the moving crust. Some of these large faults when traced to the west die out (e.g. Yushu fault) into the region of southern and central Tibet where upper crustal east-west extension, marked by N-S grabens, is dominant. Here upper crustal extension is transferred laterally to extrusion bounded by large strike-slip faults.

During the late Cenozoic, Asian crust moved from convergence in SE Tibet eastward of the eastern limit of the India indenter towhere it enters another dynamic system dominated by trench rollback in the Indoburmansubduction zone. Driving forces change laterally from shortening and thickening north of the Indian indenter to a southwestward pull from westward rollback of the Indoburmansubduction zone. This motion of the crust was also facilitated by a change in greater to lesser gravitational potential energy from the thickened Tibetan crust to the thinner crust east of the syntaxis respectively. What remains unclear is to what depth crustalmaterial is affected by these two dynamic processes and where different levels in the lithosphere may be wholly or partially decoupled from one another. Extrusion around the eastern syntaxis was preceded by Early Cenozoic extrusion of crust/lithosphere from Tibet southeastward into the Indonesian/West Pacific subduction zones. This early Cenozoic period of extrusion is more controversial but is supported by paleomagnetic evidence. However, the magnitude, location and timing of faults facilitatingextrusion and the process itself remains poorly documented. The dynamics for Early Cenozoic extrusion are somewhat similar to those for the Late Cenozoic, but are related to different geometries of the two dynamic systems, thus the geometry of thecrustal/ lithospheric motions are different from the upper crustal younger structureswhich crosscut the older ones east of the eastern syntaxis. These two major dynamic systems must be considered in any analysis of the tectonics of South East Asia.

The Longmen Shan at the eastern margin of the Tibetan plateau is another example of variations in the processes of intracontinental deformation within the Tibetan plateau. The devastating and unexpected 2008 Wenchuan earthquake has sparked numerous investigations trying to understand the tectonic setting of the earthquake. Here, the very high relief at the eastern margin of the plateau is related to the contrast in lower seismic velocities beneath the plateau, suggesting a more ductile lower lithosphere, and higher velocities beneath the Sichuan basin, suggesting a more rigid lithosphere.

Eastward flow of lower crust (and upper mantle?) from higher and thicker crust in central Tibet, an area of east-west extension expressed by north-south grabens, may have thickened the crust in eastern Tibet by eastward flow and crustal thickening beneath a passive upper crust. However, when the lower crust was unable to penetrate the less ductile crust to the east it shortened and thickened. Thus, the uplift and associated shortening in the Longmen Shan by inhibited eastward flow of ductile lower crust flow was diverted both to the north and south. Unliketo the north, in the south the flow was not inhibited and a broad gentle eastward sloping margin was developed where lower crust and its passive lid were extruded southeastward around the eastern Himalayan syntaxis. This hypothesis remains controversial. Other interpretations for the Longmen Shan have been presented, such as shortening and thickening of the crust by eastward thrusting, but such a mechanism will not explain the broad uplift of the eastern part of the plateau where much of the terrane containsminimum evidence for Late Cenozoic shortening structures. The Longmen Shan remains a very active area of research not only for tectonic analysis, but also as wake up call for potential and unrecognized seismic hazards elsewhere, for which China has many.

Northeast Tibetis an area of active shortening and strike-slip deformation expressed in the topography by narrow mountain ranges separating rhomb-shaped basins. Tectonic development began locally in the Eocene, but has become more active in Late Cenozoic time. Time-space relations indicate that northeast-striking left-lateral faults, and locally northwest-striking right lateral faults, transfer their motion into northeast to east shortening that isexpressed by linear high mountains. There is evidence that shortening within this area has changed from northeast-southwest to more east-west with time. While this area is generally elevated it does not have the high average elevation and low relief of the plateau to the south. Basin elevations generally increase to the south and the area may be in the process of achieving a high plateau like-character. Flow of ductile lower crust may just be penetrating this northeastern area.

The depth to which Tibet'slarge strike-slip faults penetrate the crust remains unclear. Many of the young large magnitude strike-slip faults have exposed metamorphic mylonitic belts along them. In some cases the faults follow earlier crustal anisotropies, such as older faults or suture zones, but others do not. Where the metamorphic mylonitic belts are observed many are present only along one side of the shear zone with lower-grade rocks on the opposite side (such as the Chong Shan and Gaoligong shear zones). This suggests that weaker and ductile lower crust has been extruded upward during major strike-slip displacement and further suggests thattheir high-grade mylonitic assemblages may be decoupled within the lower crust from still deeper lithosphere. The decoupling process is also suggested by a tectonic setting where shortening of decollement style is present on onlyone side of the fault zone. This suggests that the shear zone may be translated laterally toward the zone of shortening and terminates above the decollement zone (e.g. Xianshuihe fault south of Sichuan basin). GPS results in Yunnan suggest crustalvelocities in a South China frameworkthat are at a very high-angle to the active Red River fault indicate that the fault and its walls move southward relative to South China, but to what depth is unclear. It is not the only such strike-slip fault in China with similar non-parallel geometries with respect to relevant GPS velocities.

One tectonic feature of importance to China is a belt of early Cenozoic alkali-rich magmatic rocks that extends from central Tibet southeastward into Indochina. These rocks that have an age range from ~40 to ~20 Ma andare host to many economically rich deposits of such metals as gold, silver, copper and molybdenum. The alkali-rich rocks are the result of hot, shallow melting of a metasomatized mantle source. Several processes have been proposed for the origin of these rocks and include subduction of Himalayan lithosphere, Himalayan slab break off, delamination of the Tibetan lithosphere and lithospheric thinning. All of these processes relate to two-dimensional models, but the relations of the magmatic activity to an extrusion model suggest thata three-dimension model should be considered. This belt of alkali-rich rocks has an age range and location that may be associated with thinning of Tibetan and Southwestern China lithosphere during early Cenozoic southeastward extrusion of material from central Tibet into the subduction systems of SE Asia. Such a process may not act alone but in concert with shortening north of the India indenter and pull from rollback of subducting slabs in both Indonesian and West Pacific subduction systems.

The processes of lithospheric modification continue from initiation of post-collisionalintracontinental deformation to the present. Those processes include subduction and associated magmatism, shortening, extension, both removal and addition of lower crust and upper mantle lithosphere, heating by lithospheric thickening and consequent ductile flow. Several such processes may occur over time in any one lithospheric column, thus the nature *o*f the lithosphere is a summation of the processes that have occurred. The products of most of these deeper processes are not exposed at the surface in young orogenic systems such as the Tibetan Plateau and, thus, we must rely on geophysical tools to characterize them. A glimpse of the complicated geological character of the crust can be examined at the eastern syntaxis. Within the eastern syntaxis are exposed vertical changes in crustal composition due to underthrusting of High Himalayan lithosphere, removal of the lower part of the Gangdesebatholith, upward extrusion of deeper crust and upwelling of deep ductile crust into an extensional upper crust. This kind of scenario yields a vertically stratified crust of different crustal lithologic units and predicting what such acrustal section might look like from surface geology alone is complicated, not straightforward, and not necessarily very reliable.

The major tectonic units within the plateau exhibit great differences in upper crustal geology that probably were reflected in original differences in lower crustal and lithospheric geology. However, such differences have been modified during the processes of post-collisionalintracontinentaldeformation following their assembly into the plateau. It is an understanding of the time-space relations of these deep crustal and mantle lithosphericprocesses that is necessary to unrevel the evolution of the Tibetan plateau growth. But our present lack of sufficient understanding of a summation of these processes on a plateau-wide basis leaves many of the first order problems in plateau formation unresolved. A close working relation between geologists working on surface geology and geophysicists probing the deeper crust and mantle lithopshere with greater resoluton is necessary for further progress.

Keywords: Tibet Plateau tectonics, Plateau tectonic processes, unresolved tectonic problems.