GEOSCIENCE FRONTIERS 2(1) (2011) 57–65

available at www.sciencedirect.com
China University of Geosciences (Beijing)
GEOSCIENCE FRONTIERS
journal homepage: www.elsevier.com/locate/gsf

ORIGINAL ARTICLE

The great triangular seismic region in eastern Asia: Thoughts on its dynamic context

Xianglin Gao*, Xiaojing Ma, Xiaoli Li

Institute of Geology, China Earthquake Administration, Beijing 100029, China

Received 1 May 2010; accepted 20 September 2010
Available online 30 December 2010

KEYWORDS
Eastern Asian tectonics;
Huge triangular seismic region;
India plate;
Philippine Sea-West Pacific region;
Eurasian mantle flow

Abstract A huge triangle-shaped tectonic region in eastern Asia plays host to numerous major earthquakes. The three boundaries of this region, which contains plateaus, mountains, and intermountain basins, are roughly the Himalayan arc, the Tianshan-Baikal, and longitude line ~105°E. Within this triangular region, tectonism is intense and major deformation occurs both between crustal blocks and within most of them. Outside of this region, rigid blocks move as a whole with relatively few major earthquakes and relatively weak Cenozoic deformation. On a large tectonic scale, the presence of this broad region of intraplate deformation results from dynamic interactions between the Indian, Philippine Sea-West Pacific, and Eurasian plates, as well as the influence of deep-level mantle flow. The Indian subcontinent, which continues to move northwards at ~40 mm/a since its collision with Eurasia, has plunged beneath Tibet, resulting in various movements and deformations along the Himalayan arc that diffuse over a long distance into the hinterland of Asia. The northward crustal escape of Asia from the Himalayan collisional zone turns eastwards and southeastwards along 95°−100°E longitude and defines the eastern Himalayan syntaxis. At the western Himalayan syntaxis, the Pamirs continue to move into central Asia, leading to crustal deformation and earthquakes that are largely accommodated by old EW or NW trending faults in the bordering areas between China, Mongolia, and Russia, and are restricted by the stable landmass northwest of the Tianshan-Altai-Baikal region. The subduction of the Philippine and Pacific plates under the Eurasian continent has generated a very long and narrow seismic zone along trenches and island arcs in the marginal seas while imposing only slight horizontal compression on the Asian continent that does not impede the eastward motion of eastern Asia. In the third dimension, there may be southeastward deep

* Corresponding author. Tel.: +86 10 62009045.
E-mail address: xlgaoig@163.com (X. Gao).

Peer-review under responsibility of China University of Geosciences (Beijing).
doi:10.1016/j.gsf.2010.11.004

Production and hosting by Elsevier

mantle flow beneath most of Eurasia that reaches the marginal seas and may contribute to extension along the eastern margin of Eurasia.

1. Introduction

A map of major earthquake distribution in eastern Asia delineates a huge region relatively densely populated with earthquake epicenters (Fig. 1). It appears as a roughly equilateral triangle that is about 3500 km long on each side, has a NE-oriented central axis, and an area of 7,000,000 km^2. Geographically, it primarily includes western China and western Mongolia and has, thus, been called the China-Mongolia seismic region in a previous study (Ma and Zheng, 1981). Viewed as a plane, it has three boundaries. The southwestern boundary of the triangle lies parallel to the Himalayas. The eastern boundary lies roughly along 105°E, and tectonically along the eastern edges of South China and the Ordos block, and extending northward to LakeBaikal. The third side is the northwestern boundary, which roughly begins at the Pamirs and continues northeastward through the Tianshan Mts., the Altai, and onwards to Baikal. Since 1900, many $M \geq 7.0$ events have occurred in this triangular region. For example, the Wenchuan M_s 8.0 (M_w 7.9) earthquake of 2008, took place near the eastern boundary (Fig. 1). This broad intracontinental seismic region is characterized by widespread plateaus, mountain ranges, and intermountain basins as well as by strong tectonic deformation that has occurred during Cenozoic time, whereas the surrounding areas are almost all relatively stable or rigid blocks. From the perspective of large-scale geodynamics, this

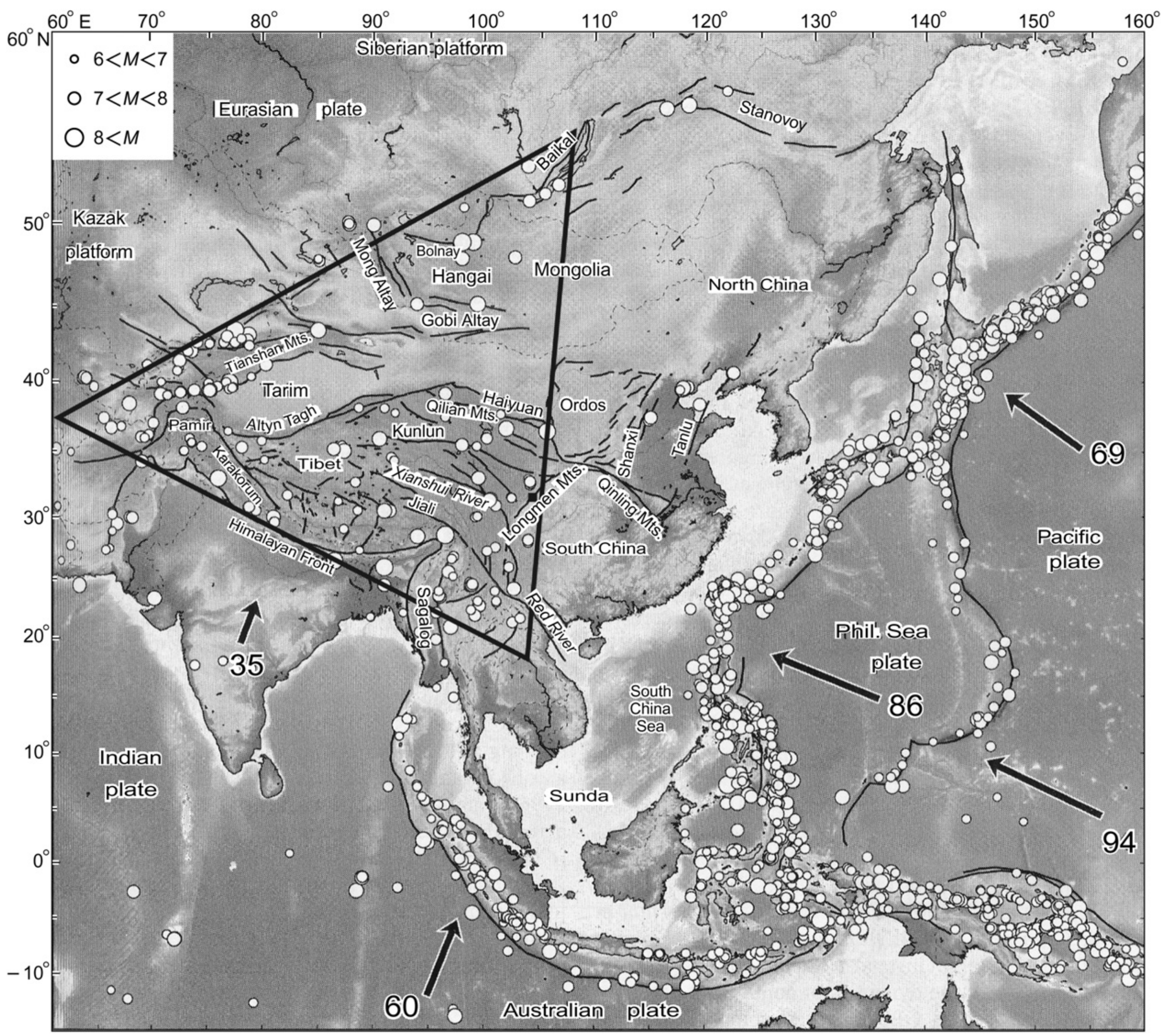

Figure 1 Map showing seismotectonics in eastern Asia (after Vergnolle et al., 2007). Circles denote earthquakes since 1973 ($M > 6$, depth < 80 km). The small box in the great triangle is the epicenter of the Wenchuan M_s 8.0 event in 2008. Black lines are major faults. Arrows are relative plate motions with respect to Eurasia (Sella et al., 2002), of which values at tails are values in mm/a.

continental deformation region reflects a triangular relationship between the Eurasian, Indian, and West Pacific-Philippine plates that can be attributed to three boundary forces, i.e. the convergence between India and Eurasia along the Himalayas, the subduction of Pacific–Philippine beneath Asia along the marginal seas, and the constraints of a stable Eurasia bordering the Pamirs, Tianshan Mts., Altai, and Baikal. Additionally, as discussed below this region is presumably subjected to the influence of mantle flow at depth.

In the last several decades, there have been numerous studies on deformation in the Tibetan plateau and Asian continent (e.g., Molnar and Tapponnier, 1975; Vergnolle, et al., 2007; Banerjee et al., 2008), most of which focus on the kinematics and dynamics of the deformation fields, particularly the competing models of block movements and continuum medium deformation, and the eastward motion of central and eastern Tibet. But aside from discussion of the Himalayas, the dynamic context of the aforementioned great triangle-shaped seismic region has been little discussed. As such, there are important issues that have not been sufficiently addressed. For example, in the east, the Pacific and Philippine plates are moving at a substantial rate toward Asia, resulting in a long and narrow seismic zone along the marginal seas, which GPS observations indicate is unable to impede the eastward movement of the Asian continent. In numerical modeling of this issue, simple velocity boundary conditions are usually adopted that assume the eastern boundary of Asia is free (no differential stress) or only affected by lithostatic pressure by gravity (Molnar and Tapponnier, 1975). There is no convincing explanation for why such an assumption is made and how it can yield modeling results consistent with observations. Furthermore, the nature of the relationship between the triangle-shaped region and the stable Eurasian interior in the north is still quite poorly understood.

In this paper, we attempt to establish a gross framework for the three borders and the deep dynamic context of this triangle-shaped seismic region in East Asia. Our attention is focused on the present-day motion of the lithosphere as shown by geological investigations, documented earthquakes, and GPS measurements. It is not concerned with the long-term geological evolution of the region. The dynamic context for the study area is summarized as follows: in the southwest, the India–Asia collision zone along the Himalayas is an active driving boundary that behaves like a powerful bulldozer, exerting a great compressive stress onto the Asian continent resulting in diffuse deformation far to the north. The eastern boundary, roughly along 105°E is largely consistent with the north-south seismic zone, separates tectonically active regions in the west from such stable and rigid blocks in the east as the Sichuan basin and South China, and restricts the eastward motion of the eastern Tibetan plateau. Much further to the south and east lie the oceanic-continent convergence zones characterized by slab subduction, which seem to exert only weak compression on the Asian margin. Beyond the northwestern boundary of the great triangle from the Pamirs to Baikal is the stable interior of the Eurasia plate, which appears to block tectonic deformation and earthquakes. As a hypothesis, we suggest that deep southeastward mantle flow from below the Eurasian continent merges with that from beneath India in central Tibet and continues eastwards, possibly leading to retreat of the West Pacific and Philippine subduction zones and extension of marginal seas. For example such a process is ongoing in the Ryukyu–Okinawa region. In the following sections, we present evidence from observations that support the above model framework. Finally we present a brief discussion on earthquake prediction in broad deformed continents such as east Asia.

2. Postcollision India–Asia convergence in the south

The collision of India with Eurasia 50 ± 10 Ma ago and the continuing convergence of the two plates following the collision have created high mountains and plateaus over an area that extends 2000–3000 km north-northeast of the northern edge of the Indian plate (Molnar and Tapponnier, 1975). The penetration of India into Eurasia creates a kinematic boundary condition on the Eurasian plate's southern margin that is responsible for the current deformation that is manifested as Quaternary faulting and active seismicity. GPS measurements made during 1995–2007 demonstrate that except for near the eastern Himalayan syntaxis, the Indian subcontinent undergoes little deformation, with north-south shortening of merely 2 ± 1 mm/a ($(0.3 \pm 0.05) \times 10^{-9}$/a); the subcontinent thus behaves as a rigid block (Banerjee et al., 2008). Currently India is moving 36–40 mm/a northward with respect to the 2500 km long Himalayan arc (Fig. 1). From INDEPTH data (Tilmann et al., 2003), a tomographic image of the crust and upper mantle beneath the Himalayas and southern Tibet has revealed a subhorizontal high-velocity zone, representing the plunging of the India plate beneath Asia. Viewed in cross section across the central Himalayas and Tibet, the India plate's leading edge has reached below the Bangong-Nujiang suture (~32°N), ~500 km north of the Main Boundary Thrust fault (MBT) in the southern Himalayas (Fig. 2). Regional study of seismic surface wave tomography suggests that the mantle at depths from ~225 to ~250 km beneath the Tibetan plateau is relatively cold. This phenomenon is interpreted to be a result of the northward underthrusting of Indian lithosphere (Priestey et al., 2006). New seismic images reveal that the horizontal distance of India's underthrusting decreases from west to east beneath the Himalayas and Tibet. For instance, in the west around the western Himalayan syntaxis, the India plate, which is marked by high seismic velocity, underlies the Himalayas and the entire plateau, reaching the southern edge of the Tarim basin. However, in the east, there is no indication for present-day underthrusting beyond the Himalayan block and the Indus–Zangbu suture (Li et al., 2008). From the perspective of thermodynamics, the northward movement of the rigid Indian subcontinent has taken form as various kinds of tectonic deformations across the Himalayas, including north-south directed crustal shortening, stratum bending and folding, thrust and strike–slip faulting, as well as east-west extension in southern Tibet (Molnar and Tapponnier, 1975). Superposition of these deformations at varied depths and different times has generated the complicated tectonic patterns we observe at present.

The eastern boundary of the India plate is the Myanmar arc (Indo–Myanmar ranges), which trends approximately north–south

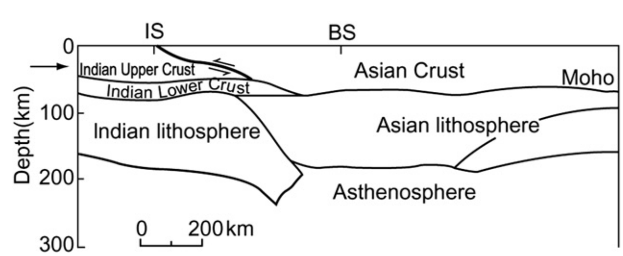

Figure 2 Sketch cross section showing the underthrusting of the Indian plate beneath Asia (Tilmann et al., 2003; Li et al., 2008). IS = Indus-Zangbu suture; BS = Bangong-Nujiang suture.

and extends northward into the northwest-southeast-trending Mishmi thrust belts of the eastern Himalayan syntaxis. Seismicity beneath this arc indicates an eastward-dipping subduction zone reaching a maximum depth of about 180 km. However, fault-plane solutions of several moderate-sized events beneath the Indo-Myanmar ranges show strike-slip faulting with P axes that plunge toward the north-northeast, nearly parallel to the strike of the arc. This trend implies that the subduction of India beneath Myanmar is highly oblique, and that the Myanmar block is subjected to north-south compression (Dain et al., 1984). GPS measurements were conducted across the Sagaing fault in central Myanmar in 1998–2000. The results show that the Myanmar block is moving northward relative to the Sunda block in the east at a rate of 32 mm/a in the global reference frame and similar to the Indian plate velocity (34 mm/a) at Bangalore in southern India. A 900 km-wide dextral shear zone separates Indian and Sunda and links to the eastern Himalayan syntaxis in the north. The right-slip Sagaing fault in central Myanmar absorbs 60% of the total deformation of the broad shear zone (Vigny et al., 2003). Because at its northeastern end the fault splits into a series of faults with only minor right-lateral offsets, it must finally terminate within the eastern Himalayan syntaxis, and its zone of clockwise rotation.

The left-slip Chaman fault is the western boundary of the India plate. It appears roughly symmetrical to the right-slip Sagaing fault, and both structures define the left and right flanks of the northward moving Indian subcontinent (Fig. 3). The Chaman fault continues into the Hindu Kush-Pamir area where the western Himalayan syntaxis, Tajik depression, South Tianshan Mts., and Tarim basin converge. This area is characterized by high elevation, thick crust, and a high concentration of intermediate-depth earthquakes. Hypocenter locations trace a Wadati–Benioff zone which dips to the north under the western and central parts of the Hindu Kush and, perhaps, southwards under the Pamir. Microearthquake studies in this region show seismicity extending to a depth of about 300 km. Two major tectonic models are suggested to explain the observed pattern of seismicity. One model suggests that two distinct slabs, the Indian and Asian slabs, are subducted beneath the region in opposite directions (Burtman and Molnar, 1993). An alternative model attributes the observed seismicity and mantle seismic structure in

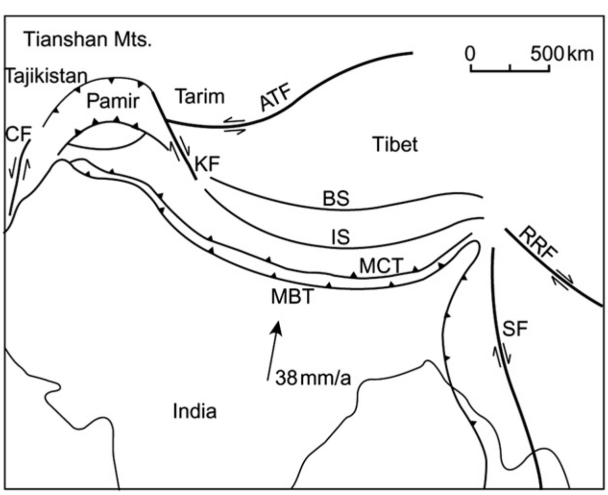

Figure 3 Sketch map showing tectonics in the Himalayan arc and its surroundings. MBT = Main Boundary thrust; MCT = Main Central thrust; IS = Indus-Zangbu suture; BS = Bangong-Nujiang suture; KF = Karakorum fault; ATF = Altyn Tagh fault; CF = Chaman fault; SF = Sagaing fault; RRS = Red River fault.

the region solely to the northward subduction of the Indian plate, which becomes overturned beneath the Pamir (Pegler and Das, 1998). GPS measurements at 90 stations during 1992–1998 reveal that the Pamir, south South Tianshan Mountains, and Tarim are all moving northwards (Reigber et al., 2001) (Fig. 3); these measurements seem not to support the model of southward subduction of the Asian continent beneath the Pamir.

The Himalayan arc terminates at both ends in syntaxes, i.e. areas where orogenic structures turn sharply around a vertical axis. These structures came about in response to several major conditions, including the plunging of the two corners of the Indian subcontinent beneath Asia, the southward extrusion of Tibetan crust (Hodges et al., 2001), and the westward extension of the Myanmar arc. At the eastern Himalayan syntaxis, the northward movement of India seems to be hampered by the eastward and southeastward motion of south Tibet, and consequently compressive deformation has spread backward to the Shillong plateau of northeastern India (Banerjee et al., 2008; Fig. 4). Near the western Himalayan syntaxis, the northward motion of India is transformed into crustal deformation by both thrust and strike–slip faulting that continues deep within the interior of central Asia.

There seems to be no doubt that the underthrusting of India beneath the Himalayas and Tibet is exerting a horizontal push at the Himalayan chain and basal shear on the Tibetan plateau, both of which produce northward displacement in the western plateau and northeastward to eastward displacement in the central and eastern plateau as shown by GPS data. The thickened and uplifted crust has generated great gravitational potential gradients that serve as one of the major driving forces for intraplate deformation (Vergnolle et al., 2007). This process has been unfolding for 50 Ma and is ongoing, affecting the tectonics of a vast area north of the Himalayas, and resulting in broad diffused deformation and seismicity in East Asia.

3. Oceanic–continental convergence in the east

GPS measurements indicate that the Australian plate is moving northward at 60 mm/a and, thus, faster than the Indian plate. The Philippine Sea and Pacific plates are moving in a northwest direction at 8 mm/a and 69 mm/a, respectively. Concurrently the Eurasian continent is moving eastwards at a slight rate (<10 mm/a, Sella et al., 2002; Fig. 4). These collective movements produce oceanic-continental convergence along the eastern margin of Eurasia, where long, deep trenches have developed. Between these trenches and the continent are a series of island arcs and marginal seas where the two oceanic plates mentioned above are being subducted beneath Eurasia. Most of the kinematic energy of the moving oceanic plates is transformed into elastic strain that leads to shallow, intermediate, and deep earthquakes, forming a long narrow seismic zone in map view. Conversely, in back-arc regions such as the Japan Sea, the East China Sea, and the South China Sea there are few major earthquakes and no indications of strong compression. On the contrary there is evidence of tectonic extension toward the ocean coinciding with the retreat of trenches in the area. A map of GPS velocities (Fig. 4) indicates that the motions of the Eurasian continent and the Philippine Sea and Pacific plates are roughly parallel to each other but moving in opposite directions. Apparently, the rapid westward motions of the oceanic plates (Philippine Sea, Pacific) do not hamper the eastward extension of the eastern Eurasian continent.

To some extent, the dynamic context around Taiwan (Fig. 5) can be used to represent the general features of tectonics in the

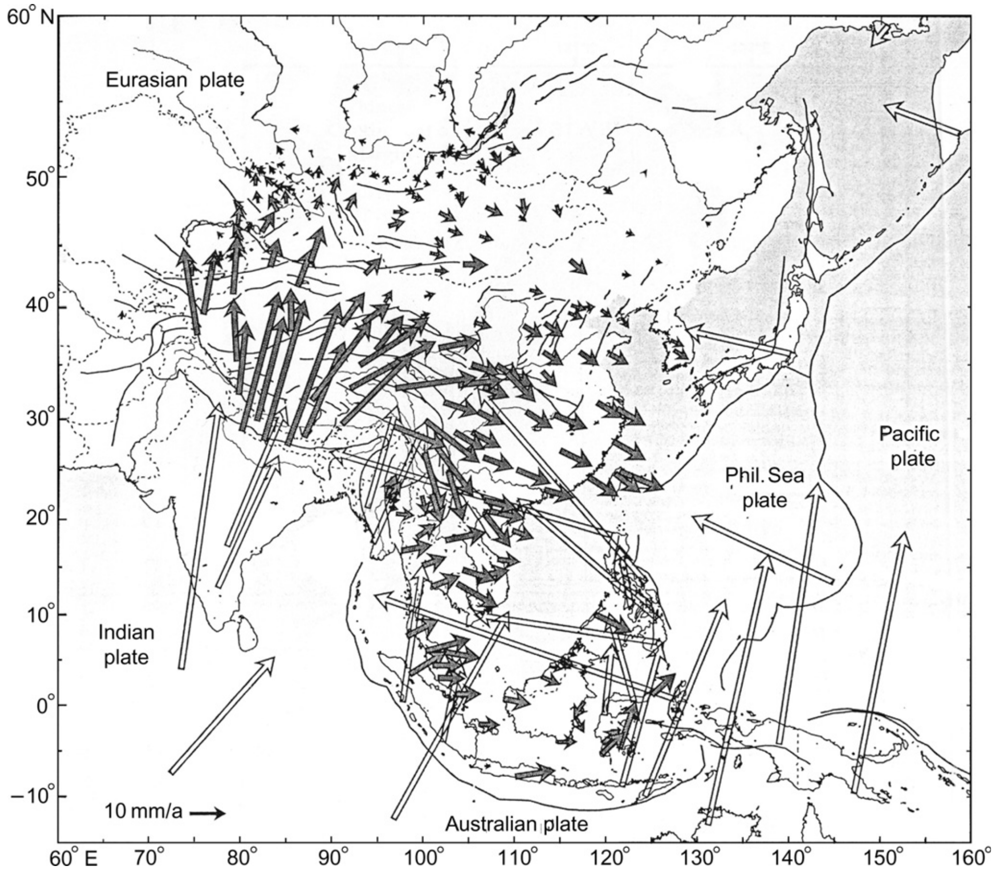

Figure 4 GPS velocities with respect to Eurasia (Vergnolle et al., 2007). Only sites with velocity uncertainty less than 1.5 mm/a are shown here. Solid arrows show GPS site velocities within Asia; open arrows showvelocities of neighboring plates.

eastern margin of Asia as a whole. South of Taiwan, the South China Sea slab of the Eurasia plate is subducted towards the east, and the N–S trending Luzon arc of the Philippine Sea plate has collided obliquely with the NE–SW trending Chinese continental margin, thus resulting in a narrow mountain belt in eastern Taiwan. In the east and northeast, the Philippine Sea plate is being subducted northwards along the Ryukyu trench, which is retreating in response to the back-arc opening of the Okinawa trough. These kinematics have been confirmed by GPS observations performed during 1995–2005 in the Taiwan region (Rau et al., 2008). It is possible that the roll back of the Philippine Sea plate at the Ryukyu trench and the nearby eastward subduction of the South China Sea have suppressed the collisional effects of the Philippine Sea plate on the Taiwan island, thus confining the compressive deformation and seismicity to the island Taiwan, with a little stress being transmitting to the west farther.

In the eastern and southeastern margins of Asia, the convergence between oceanic plates and the Asian continent produces deformation and earthquakes primarily along trenches and island arcs. The resultant compressive stress on the continent is very small, or at least smaller than that coming from the continent. Were it not for compressive stress being manifested in this way, the eastward motion of East Asia, as indicated by GPS data, cannot be explained. From the standpoint of the mechanism of dynamic balance, this long ocean-continent boundary can be imagined as a tortuous, segmented dam which experiences almost equal horizontal pressure on both sides, and which in some sections (e.g. the Ryukyu trench) is retreating toward the ocean. Thus, in many studies on the deformation of the Asian continent, this boundary is assumed to be free (e.g., Molnar and Tapponnier, 1975) or neutral with only lithostatic pressure (Houseman and England, 1993). Some interpretative tectonic models have been suggested for this boundary, such as mantle flow at depth (e.g. Flower et al., 2001). This model assumes that the horizontal force from eastward mantle flow beneath Eurasia on the subducting slab in the margin may exceed that from the westward mantle flow beneath the ocean, thus leading to trench retreat and back-arc spreading (Fig. 6), as for example the Ryukyu–Okinawa area now, and the Japan and South China Seas in early Cenozoic time. Other factors, such as slab pull (negative buoyancy) controlled by density contrast, increase of the dip of subducting slabs, and decreasing convergence rates, could also be possible reasons for extension in the eastern margins of Asia (Royden, 1993; Northrup et al., 1995). However, such factors involve changes in ocean-continent convergence with time (e.g., Royden et al., 2008), and are not be discussed in this paper.

4. Tianshan Mountains–Baikal intracontinental boundary in the north

As mentioned earlier, a NE-trending tectonic boundary connects the Tianshan Mountains and Lake Baikal and separates the stable Eurasian interior from active China-West Mongolia. Much data show conspicuous contrasts between the two sides of this boundary in topography, tectonic activity, deep structure, and

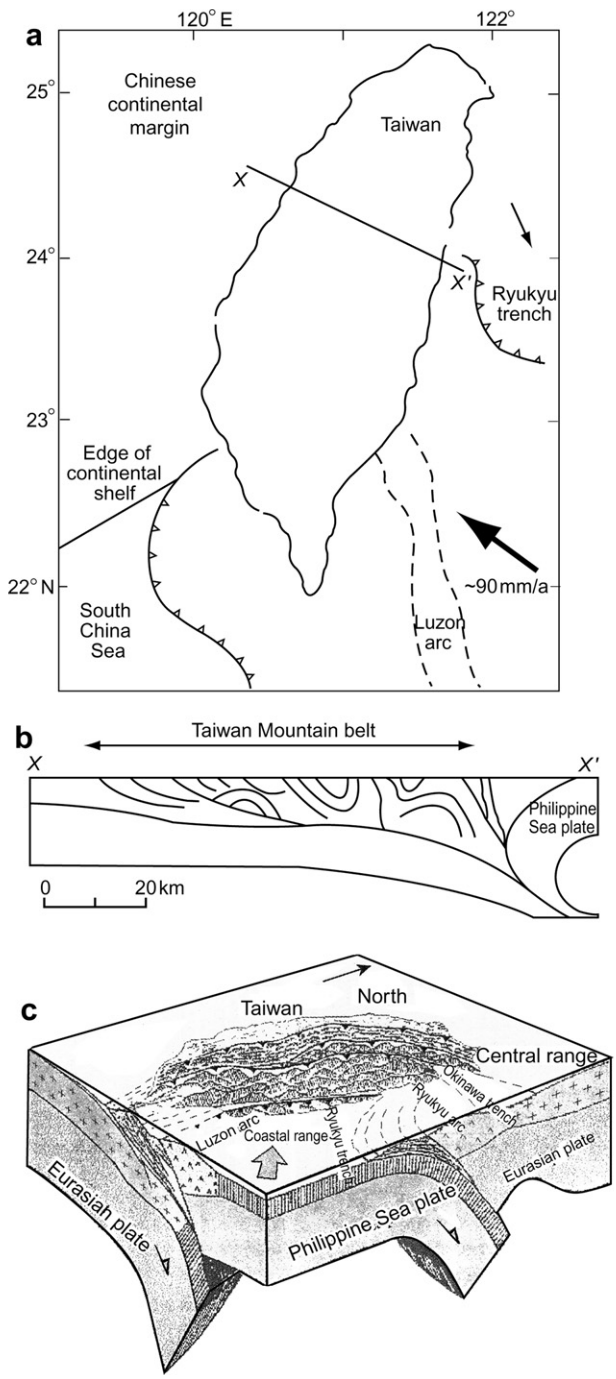

Figure 5 Sketch map showing dynamic context of Taiwan and surroundings. a) Plane view. The 90 mm/a convergence rate across the plate boundary is taken from the GPS-derived plate model REVEL (Sella et al., 2002); (b) Cross section, *XX′* in (a); (c) Sketch of 3D structure around Taiwan.

seismicity. It is inferred that it is also a boundary between the relatively cold mantle in the northwest and warm mantle in the southeast, which extends downward to a depth of ~250 km (Feng et al., 2007). GPS measurements made in West Mongolia and Baikal during 1994−2002 reveal that a NS-directed shortening rate decreases towards the north and vanishes west of the Tianshan−Baikal boundary (Calais et al., 2003). We, therefore, suggest that this zone is actually a boundary between an active deformation region and a tectonically stable region within the continent. The rigidity of the continental blocks north and west of Tianshan−Baikal terminates the NS-directed deformation related to India−Asia convergence in the south. Therefore, in dynamic models this boundary is usually regarded to be a fixed or rigid constraint (Vergnolle et al., 2007).

It is noteworthy that this boundary does not accord with trends of surface structures and deformation styles. For instance, there are no NE-trending faults or deformation zones along this boundary. Instead some EW- and NW-striking old faults in Xinjiang of China and West Mongolia, which are responsible for major earthquakes in recent times, intersect the boundary obliquely. Also, seismic activity seems to terminate at the western ends of these reactivated faults (Fig. 1). It has been speculated, based on paleomagnetic data, that this NE-trending tectonic zone may be the boundary between Siberia and Southeast Asia blocks which were wedded during Mesozoic time (Enkin et al., 1992). It is, however, not clear why there is no relative motion between the two adjacent continental blocks that can produce shear or thrust faulting such as that seen in Tibet.

5. Structure and mantle flow at depth

Crustal thickness is highly variable on both sides of the eastern boundary of the great triangle-shaped seismic region which roughly coincides with 105°E. To the west, the range and plateau areas have a relatively thick crust (>50 km), with a deeper crust-mantle interface. In the east, the crust is thinner (~40 km) and the Moho interface is relatively shallow. For instance, on a cross section starting from central Tibet and extending eastward through the Sichuan basin and South China to the margin in the East China Sea, the depth of the Moho changes from ~70 km to 30 km. Based on the mechanism of gravitational isostasy, the crust in the west is subjected to great mantle buoyancy, resulting in surface uplift. The plateau's thicker crust in the west must leave underlying mantle rock so deep and, therefore, so hot that it can flow eastwards under India's squeeze as well as gravitational force (Romanowicz, 2009).

Analysis of seismic data suggests that the base of the lithosphere is 200−250 km deep beneath the stable Eurasian continent and 80−100 km deep in oceanic regions, a sharp contrast between the depths of the continent's and ocean's uppermost mantle. Additionally, the S wave velocity structure of global upper mantle derived from seismic tomography indicates that above a depth of 400 km the Eurasian continent has high velocities indicative of relatively cold mantle rock, whereas the western Pacific lies in areas of low velocity, representing mantle rock in a hot state (Tanimoto, 1990). In conjunction with gravity anomalies, it is inferred that a boundary exists along the Tianshan-Baikal line between cold mantle beneath Siberia and hot mantle beneath East Asia. It can be further inferred that the relatively colder, and thus denser, mantle material would flow laterally towards the area of relatively hotter and less dense mantle. This inference leads to the suggestion of an eastward slow flow of mantle at depth below the Eurasian continent (Feng et al., 2007) could exert a shear stress on the base of the lithosphere (Fig. 6a). S wave splitting data (seismic anisotropy) in Tibet suggests that mantle shear occurs on subvertical foliation planes, which exhibit shear in a nearly east-west direction on the horizontal plane, correlated or consistent with the crustal strain (Holt, 2000), and also in accordance with the aforementioned effect of mantle flow. Furthermore, it is inferred from the study of mantle-source volcanic rocks that there may

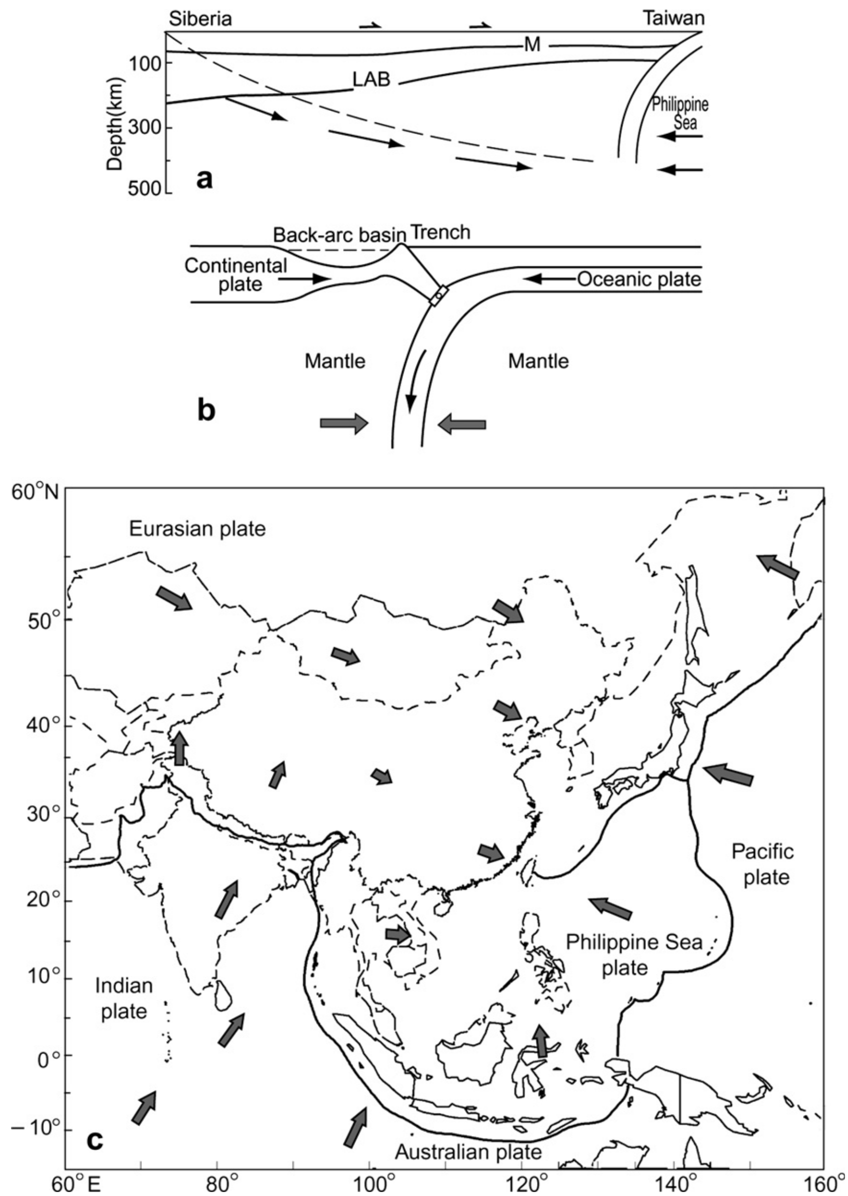

Figure 6 Sketch diagrams of the model showing assumed mantle flow beneath eastern Asia. All arrows denote mantle flow direction without sense of magnitude or rates. (a) Cross section through Asia and Taiwan, M: Moho interface, LAB: lithosphere-asthenosphere interface; (b) Cross section in eastern margin of Asia, for example at Ryukyu; (c) Plan view of assumed mantle flow at depths 200–400 km.

exist a north-south convergence of mantle flows below central Tibet that turns eastwards (Luo et al., 2006), in accordance with the displacement pattern found by GPS measurements (Fig. 4).

The inference derived from plate tectonics on the Earth's surface—that mantle is flowing slowly and continuously, and is driven by density variation associated with temperature and compositions (Manga, 2001)—seems acceptable. We suggest a model to describe mantle flow at a depth of 400 km beneath East Asia (Fig. 6c). It is based on tectonic data, seismic imaging, and GPS observations, and with the given that the crust is coupled with underlying upper mantle (especially in the stable cratons with deep roots) and that crustal motion is consistent with mantle flow in direction on a grand scale (Mooney, 1995). In the global tectonic pattern, the Eurasian continent is floating on subsiding and converging mantle flows. We propose that beneath the stable part of the Eurasian continent mantle material flows from northwest China and west Mongolia towards the southeast where it merges with northward mantle flow below the Indian subcontinent turns to the east in eastern Tibet (at roughly 95°E), and continues to flow toward the southeast — consistent with the channel flow of the lower crust there (Royden et al., 2008). In the Philippine Sea and the western Pacific, the oceanic plates there are subducted beneath the Eurasian continent where they flatten in dip, and becoming stagnant slabs above the 660 km discontinuity. Nevertheless, the upper mantle above 400 km depth in the eastern Eurasia remains relatively warm and is marked by low velocity, such as the Japan Sea, Northeast China, East China Sea, Okinawa trough and South China (e.g., Fukao et al., 2009, wherein Fig. 2). These areas are moving eastwards or southeastwards as indicated by GPS data (see Fig. 4). Therefore we speculate that the upper mantle below East Asia (approximately east of 100°E, see Fig. 6c) is also flowing slowly toward the east or southeast. Although this is a simple assumed model, at least it can help us understand to some extent why the eastern Asian continent is moving eastwards in a dynamic context of continent-continent convergence in the southwest and ocean-continent convergence in the east. To some extent, this is similar to the case that the westward motion of the North and South American plates is driven by asthenospheric flow coupled to the overlying lithosphere (Russo and Silver, 1996; Kennedy et al., 2002).

6. Discussion: earthquake prediction for a broad deformed region

Since 50 Ma the rigid Indian plate has been moving northwards at a high rate. Its 2500 km-wide leading edge has dived beneath the central Tibetan plateau. Farther north, the stable Tarim basin is also forced to move north, resulting in diffuse deformation that spreads to the Tianshan Mts. and Baikal until it is finally terminated by the more rigid and larger Siberia block. In the east, deformation is limited by the stable South China block, the Sichuan basin, the Ordos block, and western Mongolia. Consequently, a huge triangle-shaped intracontinental deformed region is produced. It is the largest in size and has the largest average elevation and crustal thickness of any such region in the world. This paper has attempted to give a brief description on its dynamic context from a three-dimensional perspective.

Numerous attempts have been made to determine the rules of temporal-spatial distribution of major earthquakes in such a broad deformed region. Except, to some extent, for the clustering character—i.e. the relative concentration of events in time and space—no convincing model with prediction values has been established (Lombardi and Marzocchi, 2007). The mechanism by which shallow quakes occur within a continent suggests that long-term slow crustal deformation can cause elastic strain to accumulate in many places, including not only the boundaries between active blocks or along major faults, but in places as well that have no indicators on the earth's surface of fault activity. Thus, within a given time period, there may be many potential sources of seismicity beneath a region where crustal stress has reached a critical state. A clustering sequence of such events may last several years to several decades in a region. For example, the four $M \geq 7.8$ earthquakes that took place in Xinjiang, China and West Mongolia during 1905−1957, were all located on nearby major faults. Strain accumulation responsible for these events must have taken place over a very long time, yet was released essentially simultaneously within a period of about 50 years, a very short time on a geological scale. Study of the correlation between these events suggests that stress transfer following each preceding earthquake might have triggered the subsequent event (Chery et al., 2001). Such a process indicates that the four seismic areas were in a critical state at the same time. Another example of clustering earthquakes is the sequence of the Mani (Tibet) M 7.3 event in 1997, the Kunlun Mountains M 8.1 event in 2001, and the Wenchuan M 8.0 in northeastern Tibet in 2008 — all close to each other in both time and space, but occurring along different faults and/or in different tectonic zones. They all originated from long-term strain accumulation in the broad deformed region, and completed — perhaps — the process of successive seismic strain release in a short time.

Retrospective studies on the Wenchuan M 8 event of 2008, confirm that long-term prediction of major earthquakes within a continent is still a formidable task (Deng, 2008). Historic seismic records, investigations of active tectonics, and geophysical explorations cannot yet provide useful quantitative indicators for forecasting the maximum magnitude and occurrence time of major earthquakes in areas with known or suspected seismic hazard. Such information is vital for disaster prevention prior to a major shock, especially in terms of determining proper construction codes and safety coefficients of buildings. In western China, many active tectonic zones or faults exhibit varied characteristics in terms of seismicity, deformation rates, and deep structure. Such variety indicates that simple models of earthquake cycles or recurrence models of major quakes (i.e. a model of elastic strain accumulation, release, accumulation again, and release again) are not applicable to the assessment of seismic risk within a continent. Indeed, no such models have been tested with sufficient data even on a single fault. For example, before the Northridge, California M 6.8 event in 1994, and the Kobe, Japan M 7.2 event in 1995, neither causative fault was seen as a threat. In September 2003, a M 8 shock struck Tokachi-Oki of northern Japan. Before this event, the 1224 operating GPS stations and approximately 1000 seismometers placed around the Japanese archipelago failed to spot any seismic hints in observed signals (Cyranoski, 2004), much as in the case of the Wenchuan, China M 8 earthquake in 2008. Scientists must acknowledge that earthquake science is advancing slowly with respect to other disciplines. Efforts in earthquake prediction, particularly in dynamic locales such as the interior of Asia, should be focused on converting scientific theories into practical technology based on instrumental observations that are aimed at the reduction of seismic hazards. It will likely take a very long time to achieve a real breakthrough.

Acknowledgement

This study was supported by the National Development Program of Major Basic Research (973 Program) (2008CB425703).

References

Banerjee, P., Bürgmann, R., Nagarajan, B., Apel, E., 2008. Intraplate deformation of the Indian subcontinent. Geophysical Research Letters 35. doi:10.1029/2008GL035468 L18301.

Burtman, P., Molnar, P., 1993. Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir. Geological Society of America Special Paper 281, 1−76.

Calais, E., Vergnolle, M., San'kov, V., Lukhnev, A., Miroshnitchenko, A., Amarjargal, S., Deverchere, J., 2003. GPS measurements of crustal deformation in the Baikal-Mongolia area (1994−2002): implications for current kinematics of Asia. Journal of Geophysical Research 108 (B10), 2501. doi:10.1029/2002JB02373.

Chery, J., Carretier, S., Ritz, J., 2001. Postseismic stress transfer explains clustering of larger earthquakes in Mongolia. Earth and Planetary Science Letters 194, 277−286.

Cyranoski, D., 2004. A seismic shift in thinking. Nature 431, 1032−1034.

Dain, A., Tapponnier, P., Molnar, P., 1984. Active faulting and tectonics of Burma and surrounding regions. Journal of Geophysical Research 89 (B1), 453−472.

Deng, Q.D., 2008. Some thoughts on the Ms 8.0 Wenchuan, Sichuan earthquake. Seismology and Geology 30 (4), 811−827.

Enkin, R.J., Yang, Z.Y., Chen, Y., Courtillot, V., 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present. Journal of Geophysical Research 97 (B10), 13953−13989.

Feng, R., Ma, Z.J., Fang, J., Wu, X., 2007. A developing plate boundary: Tianshan-Baikal active tectonic belt. Earth Science Frontiers 14 (4), 1–17.

Flower, M.F.J., Russo, R.M., Tamaki, K., Hoang, N., 2001. Mantle contamination and the Izu-Bonin-Mariana (IBM) 'high-tide mark': evidence for mantle extrusion caused by Tethyan closure. Tectonophysics 333, 9–34.

Fukao, Y., Obayashi, M., Nakakuki, T., 2009. Stagnant slab: a review. Annual Review of Earth and Planetary Sciences 37, 19–46.

Hodges, K.V., Hurtado, J.M., Wipple, K.X., 2001. Southward extrusion of Tibetan crust and its effect on Himalayan tectonics. Tectonics 20 (6), 799–809.

Holt, W.E., 2000. Correlated crust and mantle strain fields in Tibet. Geology 28 (1), 67–70.

Houseman, G., England, P., 1993. Crustal thickening versus lateral expulsion in the India-Asian continental collision. Journal of Geophysical Research 98 (B7), 12233–12249.

Kennedy, L.A., Kelly Russell, J., Kopylova, M.G., 2002. Mantle shear zones revisited: the connection between the cratons and mantle dynamics. Geology 30 (5), 419–422.

Li, C., van der Hilst, R.D., Meltzer, A.S., Engdahl, E.R., 2008. Subduction of Indian lithosphere beneath the Tibetan plateau and Burma. Earth and Planetary Science Letters 274, 157–168.

Lombardi, A.M., Marzocchi, W., 2007. Evidence of clustering and nonstationarity in the time distribution of large worldwide earthquakes. Journal of Geophysical Research 112 (B02303). doi:10.1029/2006JB004568.

Ma, Z.J., Zheng, D.L., 1981. The central axis zone and its seismicity in China mainland and Monglolia. Earthquake Research 4 (4), 421–436.

Luo, Z.H., Mo, X.X., Hou, Z.Q., Deng, W.M., Wang, J.H., Zhao, Z.D., Yu, X.H., Li, J.P., 2006. An integrated model for the Cenozoic evolution of the Tibetan plateau: constraints from igneous rocks. Earth Science Frontiers 13 (4), 196–211.

Manga, M., 2001. Shaken, not stirred. Nature 410, 1041–1043.

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

Mooney, W.D., 1995. Continental roots go with the flow. Nature 375, 15.

Northrup, C.J., Royden, L.H., Burchfiel, B.C., 1995. Motion of the Pacific plate relative to Eurasia and its potential relation to Cenozoic extension along the eastern margin of Eurasia. Geology 23 (8), 719–722.

Pegler, G., Das, S., 1998. An enhanced image of the Pamir-Hindu Kush seismic zone from relocated earthquake hypocenters. Geophysical Journal International 134 (2), 573–595.

Priestey, K., Debayle, E., McKenzie, D., Pilidou, S., 2006. Upper mantle structure of eastern Asia from multimode surface waveform tomography. Journal of Geophysical Research 111 (B10304). doi:10.1029/2005JB004082.

Rau, R.J., Ching, K.E., Hu, J.C., Lee, J.C., 2008. Crustal deformation and block kinematics in transition from collision to subduction: global positioning system measurements in northern Taiwan, 1995–2005. Journal of Geophysical Research 113 (B09404). doi:10.1029/2007JB005414.

Reigber, C., Michel, G.W., Galas, R., Angermann, D., Klotz, J., Chen, J.Y., Papschev, A., Arslanov, R., Tzurkov, V.E., Ishanov, M.C., 2001. New space geodetic constraints on the distribution of deformation in Central Asia. Earth and Planetary Science Letters 191, 157–165.

Romanowicz, B., 2009. The thickness of tectonic plates. Science 324, 474–476.

Royden, L.H., 1993. The tectonic expression of slab pull at continental convergent boundaries. Tectonics 12 (2), 303–325.

Royden, L.H., Burchfiel, B.C., van der Hilst, R.D., 2008. The geological evolution of the Tibetan plateau. Science 321, 1054–1058.

Russo, R.M., Silver, P.G., 1996. Cordillera formation, mantle dynamics, and the Wilson cycle. Geology 24 (6), 511–514.

Sella, G.F., Dixon, T.H., Mao, A., 2002. REVEL: a model for recent plate velocities from space geodesy. Journal of Geophysical Research 107 (B4). doi:10.1029/2000JB00033.

Tanimoto, T., 1990. Long-wavelength S-wave velocity structure throughout the mantle. Geophysical Journal International 100, 327–336.

Tilmann, F., Ni, J., INDEPTH III Seismic Team, 2003. Seismic imaging of the down welling Indian lithosphere beneath central Tibet. Science 300 (5624), 1424–1427.

Vergnolle, M., Calais, E., Dong, L., 2007. Dynamics of continental deformation in Asia. Journal of Geophysical Research 112 (B11403). doi:10.1029/2006JB004807.

Vigny, C., Socquet, A., Rangin, C., Chamot-Rooke, N., Pubellier, M., Bouin, M., Bertrand, G., Becker, M., 2003. Present-day crustal deformation around sagaing fault, Myanmar. Journal of Geophysical Research 108 (B11), 2533. doi:10.1029/2002JB001999.