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Magnetotelluric Studies of Active Continent–Continent Collisions

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Abstract Continent–continent collisions are an important tectonic process and have played a fundamental role in the evolution of the modern continents. A combination of geological and geophysical data has provided new constraints on the structure and temporal evolution of these orogens. Magnetotelluric (MT) studies have been an important part of these studies since they can constrain the fluid content and thermal structure which are key parameters for defining the rheology of the crust and upper mantle. MT studies of the Himalaya have defined the geometry of active faults associated with continued plateau growth. Orogen scale MT studies have shown that both the India–Asia collision (Tibetan Plateau and Himalaya) and the Arabia–Eurasia collision (Eastern Anatolia) have developed a low resistivity mid-crustal layer with upper surface at 10–20 km that is likely due to a combination of partial melt and associated aqueous fluids. The properties of this layer are consistent with a strength contrast that permits crustal flow over geological timescales. The upper mantle from the Moho to at least 100 km beneath both Northern Tibet and the Anatolian Plateau is characterized by low resistivity values (10–30 Ωm) indicating the presence of shallow asthenosphere. Future integrated seismic and MT studies of collision zones are needed fully to explore the 3D structures associated with deformation and further constrain geodynamic models.

Keywords Geophysics · Tectonics · Magnetotellurics · Tibetan plateau · Continent–continent collision · Anatolian plateau

1 Introduction

Plate tectonics has provided a unifying explanation for many diverse geological and geophysical observations. The idea of rigid plate motion with narrow zones of deformation gives an accurate description of plate boundaries such as mid-ocean ridges and transform faults. Convergent margins where oceanic crust is subducted can also exhibit narrow zones

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of deformation extending from the surface to depths in excess of 600 km. However, when both colliding plates contain continental crust, continued subduction is not possible owing to the lower density of continental crust compared to oceanic crust. If the region of continental crust on one plate is relatively small, terrane accretion can occur, with the arc jumping to the outboard side of the accreted terrane (Rotstein and Kafka 1982). Terrane accretion was first recognized in the Southern Canadian Cordillera (Coney et al. 1980) and contributes to the growth of the continents over time. It occurs today in the Northern Canadian Cordillera as the Yakutat block is accreted to North America (Mazzotti and Hyndman 2002). If the accreted block is continental in size then a continent–continent collision will occur and deformation can extend over horizontal distances of thousands of kilometres, and the plate boundary becomes a broad region rather than a narrow zone. Continent–continent collisions are important because they have led to the assembly of the modern continents, have influenced global weather patterns such as the monsoon (Molnar et al. 1993) and modified the composition of seawater (Edmond 1992; Quade et al. 1997). As knowledge of the Earth system improves, it is also becoming clear that interactions occur in the opposite direction with climate influencing tectonics (Whipple 2009).

The tectonic processes associated with mountain building during continent–continent collisions have been the subject of research for the last century. After the proposal of continental drift by Wegener (1912), geological studies of the European Alps and other mountain belts by Argand (1924) and others gave evidence that these features represented the locations of collisions that were characterized by ductile deformation. Argand (1924) proposed that large scale underthrusting had occurred in both the India–Asia and Arabia–Eurasia collisions as shown in Figs. 13 and 14 of his monograph (Fig. 1). Since the acceptance of global plate tectonics in the 1960s, the crustal and upper mantle structure of continent–continent collisions has been studied with a range of geophysical and geological techniques. These studies have revealed many details of their present day structure and tectonic history.

Magnetotelluric (MT) imaging of the crustal and upper mantle structures has played an important role in this characterization process. This review will focus on the two most active collision zones which are (1) the India–Asia collision that has formed the Tibetan Plateau and Himalaya and (2) the Arabia–Eurasia collision that has formed the Anatolian-

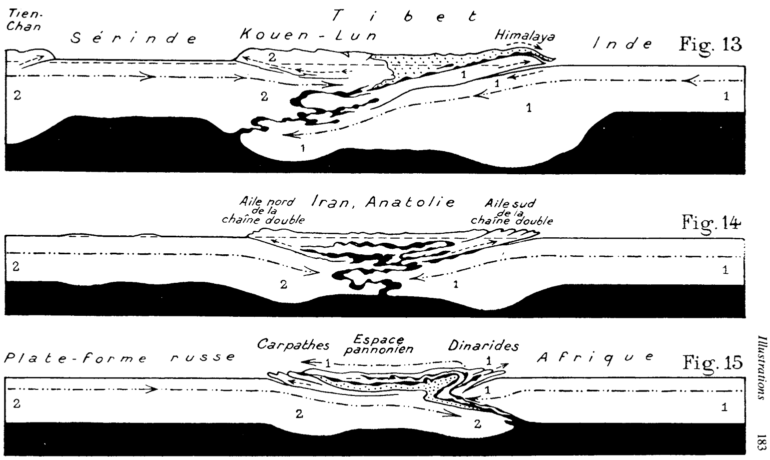

Fig. 1 Cross-sections of the India–Asia and Arabia–Eurasia collisions from Argand (1924)

Iranian Plateau. Collision zones at a later stage of evolution, such as the European Alps and Pyrenees are also discussed. The Altiplano-Puna is a high plateau in the Central Andes with many similarities to the Tibetan Plateau. However, it has formed in a subduction zone setting and reveals that several tectonic processes can build a high elevation plateau. Ancient continent–continent collisions are clearly recorded in the geological record over the last 4 Ga. Magnetotelluric studies of these features have played a major role in defining their structure and history (e.g. Boerner et al. 2000; Jones et al. 2005; Hjelt et al. 2006) but are not discussed in detail in this review.

2 Geodynamic Models for Collision Zones

A broad range of geodynamic models has been developed to explain the structure and temporal evolution of continent–continent collisions. Some of these models have been developed in response to new geological and geophysical observations, while, on other occasions, specific field studies have been undertaken to test the predictions made by models.

2.1 Tectonic Processes in Collision Zones

Argand (1924) presented one of the first hypotheses to explain the formation of mountain belts and plateau by continent–continent collisions. Based on field observations in the Swiss Alps, he developed models for the entire Alpine-Himalayan orogenic belt, including Eastern Anatolia and the Tibetan Plateau. These models suggested that the crust had undergone ductile deformation during mountain building. Argand's models for the Alpine-Himalayan orogenic belt also proposed that the crust had been thickened by underthrusting of the colliding continent in each orogen (Fig. 1). In Anatolia he envisioned underthrusting from both the North and the South. Several other processes have been suggested for collisional tectonics and are illustrated in Fig. 2 for the Arabia–Eurasia collision in Eastern Anatolia.

Continent–continent collisions begin with subduction of an oceanic plate beneath a continental plate causing an ocean basin to close (Rotstein and Kafka 1982; Fig. 2a). Continental crust can be temporarily subducted to depths in excess of 80 km where it is metamorphosed into ultra-high pressure (UHP) rocks bearing characteristic minerals such as coesite. However, the continental crust cannot be permanently subducted owing to its buoyancy and the UHP rocks will be rapidly exhumed and exposed at the surface. The Tso Morari dome in the Indian Himalaya is one of the best examples of this phenomenon (Leech et al. 2005). Warren et al. (2008a, b) describe numerical modelling of this process that explains the surface exposures of UHP rocks at the surface. At some point in the temporal evolution, the subducting slab breaks off at depth, as it is not strong enough to transmit the necessary force to subduct the buoyant continental crust. The detached slab can sometimes be detected with teleseismic data and detached slabs have been reported from beneath the Alps, Eastern Anatolia and Tibetan Plateau (Kosarev et al. 1999).

Underthrusting of one plate beneath the other is one way to produce a thickened crust. Dewey and Burke (1973) described geological observations of ancient mountain belts such as the Variscides where crustal melting was observed, and proposed that distributed horizontal shortening could also result in vertical thickening of the crust (Fig. 2b). Sengor and Kidd (1979) gave additional support for this type of deformation based on the observation that active shortening was occurring over a significant portion of the Anatolian Plateau.

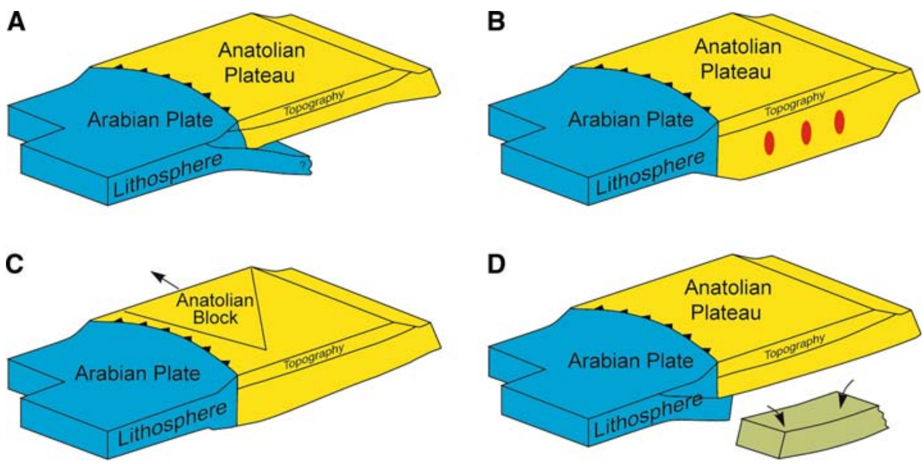

Fig. 2 Tectonic processes that may contribute to the overall mass balance and deformation in continent–continent collisions illustrated for the Anatolian Plateau. **a** Illustrates how subduction occurs on the early stages of collision; **b** Thickened crust can result from horizontal shortening (Dewey and Burke 1973); **c** illustrates how horizontal motion may contribute to the overall mass balance (McKenzie 1972), **d** lithospheric material may be removed through delamination (Molnar et al. 1993). Individual processes are described in the text in detail

Horizontal motion can be important in achieving a mass balance and was first proposed by McKenzie (1972) for Anatolia based on the strike-slip motion on the North and East Anatolian faults (Fig. 2c). The presence of similar faults in Northern Tibet (Altyn Tagh and Kunlun faults) and South West China (Red River Fault and others) led Tapponier et al. (1982) to suggest that crustal extrusion was also significant in the India–Asia collision. Strike slip motions have also been documented in the Eastern Alpine orogeny (Selverstone 2005; Robl et al. 2008).

Other tectonic processes that may be significant in continent–continent collisions involve the upper mantle. A thickened lithosphere becomes gravitationally unstable and its lower portion can detach and sink into the asthenosphere (Fig. 2d) and lead to localized upper mantle convection that may remove the lithospheric upper mantle (Molnar et al. 1993).

Crustal flow may be an important process in continent–continent collision zones and two distinct patterns have been proposed. In the first type of flow, radiogenic heat production can lead to mid-crustal melting in a thickened crust. This can generate a weakened layer that can propagate horizontally under certain conditions. If coupled to uplift and erosion, this may result in the exposure of formerly molten mid-crustal rocks at the surface (Beaumont et al. 2001, 2004). However, not all geological studies in the Himalaya and Karakorum support the idea of channel flow, with deformation being proposed to occur through brittle rather than ductile processes (e.g. Kohn 2008). The second type of crustal flow suggests that the elevated topography of a plateau causes outward flow that may accompany extrusion of rigid upper crustal blocks. This lower crustal flow acts to hydraulically thicken the crust in the adjacent areas, but the crustal flow channel does not reach the surface (Clark and Royden 2000; Clark et al. 2005).

The individual tectonic processes listed above are not mutually exclusive, and a combination of several processes is required to account for the deformation observed in continent–continent collision zones. An important goal for geodynamic research is to determine what combination of processes is active today, and to determine how this has changed over the history of the orogen (Johnson 2002; Replumaz and Tapponnier 2003).

2.2 Temporal Evolution

Jamieson and Beaumont (1989) discussed the temporal evolution of orogens with three distinct stages. The first was a constructive phase that occurs as the plateau gains elevation. In the second stage a steady state is achieved and both the India–Asia and Arabia–Asia collisions appear to be in this stage, although Edwards and Grasemann (2009) present an alternative view on this topic. The third stage of orogen evolution occurs when deformation rates reduce and the rate of mass input decreases with erosion and collapse becoming dominant, as currently observed in the European Alps (Selverstone 2005).

The style of deformation in collision zones can be categorized in a number of ways. For example, it is still not clear in many orogenic belts if deformation is confined to a thin upper crustal layer (thin-skinned) or whether it involves the entire crust and upper mantle (thick-skinned). Deformation models can also be classified on the basis of whether they represent brittle deformation, with surface motion characterized by brittle motion of a set of rigid blocks (Tapponnier et al. 1982) or by distributed continuous deformation (England and Molnar 1997). As will be described below, MT is able to provide first order constraints on the rheological properties of the crust and mantle, and can aid our understanding of which mechanisms are at work.

3 Electrical Resistivity and the Rheology of Fluid Bearing Rocks

Magnetotellurics (MT) complements seismic, gravity and magnetic studies of the processes occurring in continental dynamics. MT data can provide images of electrical resistivity, a parameter which is particularly sensitive to (a) the temperature and (b) the presence of highly conductive phases such as water, melt, sulphides or graphite. Some of these phases can also have a profound impact on the strength of the material. Thus measurements of electrical resistivity can be used to constrain the rheology of the crust and mantle. To make this link, two questions must be addressed. Firstly the electrical resistivity should be related to the fluid content, and secondly the fluid content must be linked to rheology.

3.1 Variation of Bulk Electrical Resistivity with Fluid Content

The first question requires that the bulk resistivity measured with MT is related to the amount of fluid, type of fluid and temperature of the rock. This type of analysis is associated with non-uniqueness and requires careful laboratory observations. It should be noted that resistivity values measured in laboratory experiments and resistivity values derived from MT surveys are not always in agreement. The two types of fluid widely encountered in regions of active deformation are (a) partial melts and (b) aqueous saline fluids. Both these liquids have a resistivity that is much lower than that of the rock matrix, and thus the amount of fluid, the resistivity of the fluid and the geometric distribution of fluid within the rock will control the overall (bulk) resistivity of the rock. It should also be noted that both aqueous fluids and melt are often found together in geothermal regions, so some combination of the two fluids is likely responsible for regions with low resistivity (Li et al. 2003). Archie's Law is one of a number of empirical equations used to relate the resistivity of the rock to the fluid content. This states that the resistivity of a fluid saturated rock, ρ, is given by:

$$\rho = C\rho_f \Phi^{-m}$$

where ρ_f is the fluid resistivity, Φ is the fluid content and m the cementation factor that contains information about the fluid distribution within the rock. C is an empirical factor that is sometimes needed to reconcile Archie's Law with resistivity measurements.

Very few experimental studies of the resistivity of partial melts have been made. Roberts and Tyburczy (1999) investigated a mixture of olivine and mid-oceanic ridge basalt (MORB), with the melt fraction being controlled by the temperature. This study showed that Archie's Law could be used to understand the resistivity of partial melts with $C = 0.73$ and $m = 0.98$, implying good interconnection of the grain boundary melt. The approach of Roberts and Tyburczy (1999) has the complication that the melt composition varied with temperature, and only a limited range of melt fractions can be considered. A novel approach to this problem was presented by ten Grotenhuis et al. (2005) who studied the melt geometry in a synthetic olivine sample at atmospheric pressure, with the melt fraction controlled by the addition of glass. Analysis of quenched samples showed that effective interconnection occurs at melt fractions in the range 1–10%. The resistivity of the samples was well described by Archie's Law with constant, $C = 1.47$ and cementation factor $m = 1.3$, which represents a lower degree of interconnection than in the study of Roberts and Tyburczy (1999). The discovery of the crustal low resistivity zone beneath Southern Tibet has motivated new studies of the physical properties of partial melts. Laboratory studies by Gaillard et al. (2004) showed that the resistivity of hydrous granitic melts at the appropriate pressure and temperature was in "perfect agreement with those inferred from MT data" beneath Southern Tibet.

Aqueous fluids dominate the bulk resistivity of sedimentary rocks. This can be quantified with Archie's Law, which is an empirical relationship that was derived for the interpretation of well logs in sedimentary rocks (Archie 1942). Application of Archie's Law to mid and lower crustal rocks requires knowledge of how the fluid will be distributed geometrically in the pore space. This is controlled by the dihedral angle, which is a function of the surface energy of the pore fluid and rock grain. A dihedral angle less than 60° is needed for the fluid to form an interconnected network along the grain boundaries. Watson and Brennan (1987) showed that under lower crustal conditions the dihedral angle was expected to be close to 60°. Holness (1992) and Holness (1993) describe experimental evidence for the dihedral angle to fall below 60° as the pressure increases. These previous experiments were for undeformed samples and Tullis et al. (1996) showed that, in samples subject to shear stress, interconnection was greatly enhanced, resulting in weakening. This type of feedback mechanism can lead to strain localization in the lower crust or upper mantle, with a broad zone of deformation at a low strain rate developing into a narrower region with higher strain rates. Hyndman and Shearer (1989) interpreted lower crustal resistivities and showed that if Archie's Law is used to compute the porosity of the lower crust, assuming that aqueous fluids are the cause of the low resistivity, then a value of m in the range 1.5–2.0 is appropriate. Note that this is higher than the value of m derived for partial melts, suggesting that aqueous fluids are less well connected than partial melts at mid to lower crustal conditions.

3.2 Variation of Rheology with Fluid Content

The second question to be answered is how the fluid content influences the rheology. This requires laboratory measurements of the mechanical properties of rocks as the fluid content and temperature is varied. These experiments are generally made at relatively high strain rates and the results must be extrapolated to the much lower strain rates that characterize continental deformation. Several recent studies have provided empirical relationships between the electrical and mechanical properties of crustal and upper mantle rocks. As in the previous section the fluid can be partial melt or aqueous fluids.

As the melt fraction increases the strength of the rock will be reduced. Arzi (1978) showed that a significant reduction in the strength of a rock occurred when a rheologically critical melt percentage (RCMP) of around 20% was reached and the rock essentially became a liquid. Renner et al. (2000) developed an empirical relationship for the RCMP in terms of the ambient conditions. The change in rock strength at the RCMP can be several orders of magnitude. However, the largest absolute change in strength occurs as the melt fraction varies from 0 to 10%. Rosenberg and Handy (2005) compiled a number of earlier laboratory studies and showed that, for granite and aplite melts, this loss of strength at low melt fraction can exceed an order of magnitude.

The presence of an aqueous fluid can also influence the rheological properties of crustal materials (see review by Burgmann and Rosen 2008). As with partial melts, the effect of aqueous fluids will be much greater if the fluid phase is interconnected, and knowledge of the dihedral angle is important.

Graphite can also weaken a rock and has been suggested as a cause for the spatial coincidence of high conductivity layers and earthquakes (Glover and Ádám 2008) in certain stable regions of the continents. Could graphite also contribute to the elevated conductivity in active orogens? Graphite is often locally found in exhumed shear zones in orogenic belts such as the European Alps (Losito et al. 2001) and also in large scale features in ancient orogens such as exhumed mid-crustal levels of many regions of the Fennoscandian Shield (Hjelt et al. 2006). Graphite may be able to explain the elevated conductivity in ancient collision zones, which implies that carbon was present when the orogen was formed. However, it is not clear if the carbon was present as graphite during the actual collision, or whether the graphite was formed at a later stage of tectonic evolution.

4 India–Asia Collision Zone

4.1 Geological Background

The surface features and geology of Tibet were first investigated by explorers during the nineteenth and early twentieth centuries, and systematic geological mapping now covers most of the Tibetan Plateau (Yin and Harrison 2000). The pre-collision structure of Asia comprised a series of terranes that were accreted to the southern margin of Asia during the Cenozoic (Fig. 3). The Songpan-Ganze, Qiangtang and Lhasa terranes were accreted to Asia with subduction jumping to the southern margin of the accreted terrane in each case. As the Tethyan Ocean closed, subduction of oceanic crust beneath the Lhasa block was responsible for the volcanism that formed the Gandese batholith. The collision between India and Asia occurred along the Indus–Tsangpo suture (ITS), beginning in the West and, with the arrival of a continent sized crustal block (Indian subcontinent), the tectonic style changed completely. Reasonable estimates of the age of collision extend from 45 to 70 Ma (Aitchison et al. 2007; Wang et al. 2008). This date is important for geodynamic studies as the amount of time that has elapsed since collision provides an important constraint on the mechanisms that could have built the Tibetan Plateau. The pre-collision topography of the southern margin of Asia is important to the overall mass balance calculations of the collision (Johnson 2002). Murphy et al. (1997) suggest that elevations could have already been as high as 3–4 km over most of the Lhasa block prior to the closure of the Tethys Ocean.

The Tibetan Plateau grew as the India–Asia collision continued and a steady state developed (see Sect. 2.2). Geodynamic arguments suggest that a maximum elevation of around 5 km can be sustained through a dynamic balance between uplift and erosion (Molnar et al. 1993). Continued convergence between India and Asia provides an input of mass into the collision zone and results in continued lateral growth of the Tibetan Plateau to the North East (Tapponier et al. 2001; Meyer et al. 1998). This is characterized by thrust-faulting at low elevations, and collapse at higher elevations as the Tibetan Plateau undergoes extension with normal faulting (Cook and Royden 2008). The East–West extension has formed a series of North–South trending rift zones in Southern Tibet (Armijo et al. 1986) including the Yadong-Gulu rift that was the location of INDEPTH work in Southern Tibet (Nelson et al. 1996; Chen et al. 1996). Dating of motion on these normal faults shows that extension has been occurring in the Southern Tibetan Plateau for at least the last 14 Ma (Coleman and Hodges 1995). Molnar et al. (1993) suggested that lithospheric delamination could have caused a sudden increase in the elevation of the Tibetan Plateau around 8 Ma. Paleo-altimetry studies challenge this view and show that Central Tibet has been at an elevation of more than 4 km for the last 35 Ma, with no evidence for a period of rapid uplift, as predicted by a delamination event (Rowley and Currie 2006).

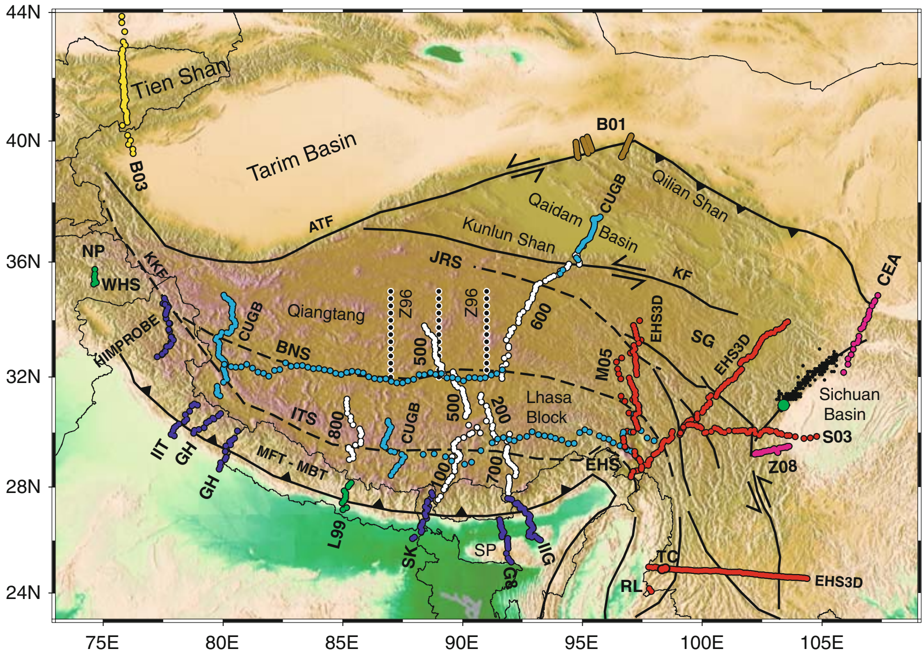

Fig. 3 Regional scale map of the India–Asia collision zone showing major tectonic features discussed in the text. MT surveys are identified in Table 1. Tibetan Plateau is the region bounded by the ATF and MFT. Tectonic features are: *SP* Shillong Plateau, *ATF* Altyn Tagh Fault, *KF* Kunlun Fault, *KKF* Karakorum Fault, *JRS* Jinsha River Suture, *BNS* Bangong-Nuijiang Suture, *ITS* Indus Tsangpo Suture, *EHS* Eastern Himalayan Syntaxis, *MFT* Main Frontal Thrust, *MBT* Main Boundary Thrust, *WHS* Western Himalayan Syntaxis. *Large green circle* shows the epicentre of the May 12 2008 Wenchuan earthquake and the *small black dots* denote aftershocks in the Longmenshan

4.2 Seismic, Gravity and Magnetic Studies of the India–Asia Collision Zone

The first geophysical study of a continent–continent collision was the geodetic study of Airy (1855) who used measurements of pendulum deflections to infer that the crust was thicker beneath the Tibetan Plateau than under India. Airy's hypothesis predicts a crustal thickness of 70–80 km for the Southern Tibetan Plateau, which is in good agreement with estimates derived from seismic exploration (Hirn 1984; Zhao et al. 1993). Regional seismic networks deployed in the 1970s and 1980s provided the first information about the crust and upper mantle structure beneath the Himalaya and Tibetan Plateau. Studies of compressional and shear waves travelling horizontally just below the Moho in the uppermost mantle (termed P_n and S_n) by Ni and Barazangi (1983) suggested that the Indian plate was underthrusting only the southern half of the Tibetan Plateau. The northern half of the Tibetan Plateau was underlain by a zone of shear wave attenuation in the upper mantle which suggested that the asthenosphere was present at shallow depth.

The first modern geophysical studies of the Tibetan Plateau were made under the auspices of the Sino-French collaboration in the 1980s. Controlled source seismic data from this project gave confirmation that the crust was very thick in Southern Tibet, locally exceeding 70 km (Hirn et al. 1984). Magnetotelluric data showed that the crust contained zones of low resistivity at depths of 10–20 km (Yuan et al. 1985; Pham et al. 1986). Combined with measurements of elevated heat flow, these zones were interpreted as being due to partial melt at mid-crustal depths (Francheteau et al. 1984).

In 1991 project INDEPTH (INternational DEep Profiling of Tibet and Himalaya) was initiated as a collaboration between Chinese and American scientists. INDEPTH produced the first deep sounding seismic reflection profile in Tibet (Zhao et al. 1993) and imaged a strong reflection that dipped northward at 10–15°. This feature was named the Main Himalayan Thrust (MHT) and could be extrapolated to the surface in the Himalayan Foothills where India actively underthrusts the Himalaya today (Nelson et al. 1996) on the presently active Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT). Continued INDEPTH seismic exploration to the North revealed that the top of the Indian Plate could not be traced beyond the Indus-Tsangpo Suture (ITS). To the North of the ITS several negative polarity seismic bright spots were observed that suggested the presence of fluids in the crust at a depth of 15–20 km (Nelson et al. 1996; Brown et al. 1996). Teleseismic data have been very effective at deeper imaging of the crust and upper mantle in Central and Northern Tibet. Receiver functions show a southward dipping interface beneath Northern Tibet (Kind et al. 2002) that supports the concept that Asian lithosphere is being subducted beneath Northern Tibet. Tomography shows a steeply dipping high velocity zone that has been interpreted as the Indian Plate subducting beneath the Bangong-Nuijiang suture in Central Tibet (Tilmann et al. 2003). This tomography study also confirmed the presence of a shallow asthenosphere beneath Northern Tibet that was first detected by Ni and Baranzangi (1983). Kosarev et al. (1999) used body wave tomography to image the detached Indian slab beneath Tibet. Surface wave tomography provides an alternative technique for imaging the upper mantle and determines the properties of the crust and mantle along a ray path between a pair of seismic stations. The depth variations can be constrained by the period dependent depth of investigation of Rayleigh waves. These studies show that the anomalous low velocities in the asthenosphere beneath Northern Tibet do not extend to significant depths, and high velocities are present beneath depths of 150 km (Priestly et al. 2006). This structure is consistent with the hypothesis of Tapponnier et al. (2001) who proposed that multiple underthrust slabs have thickened the Tibetan lithosphere.

Global positioning system (GPS) data collected in Tibet have confirmed that the 4 cm per year motion of India relative to Eurasia is accommodated across the entire Tibetan-Himalayan orogen, with no major velocity change across fault zones or sutures within the Tibetan Plateau (Zhang et al. 2004). In the Himalaya the GPS data show that convergence occurs on the MBT and MFT. Geological studies in the High Himalaya have mapped the Main Central Thrust (MCT) which was a previously active thrust. The MBT, MFT and MCT all appear to join the Main Himalayan thrust at depth.

GPS data also define the extrusion of South East Asia, with the surface moving with a semi-circular motion around the Eastern Himalaya syntaxis (Shen et al. 2005). In Northern Tibet, GPS data show that the Altyn Tagh and Kunlun Faults move at around 20 mm per year (Bendick et al. 2000). The velocity determined from offsets of geological markers is higher (Meriaux et al. 2003) and has led to a lengthy debate about the rate of motion on the Altyn Tagh Fault. However, when analysing GPS data it must always be remembered that instantaneous velocities are being measured, while geologically derived estimates average over a number of earthquake cycles. Recent studies by Cowgill et al. (2009) appear to have reconciled these differing observations in favour of a slow slip rate.

Gravity data from the Tibetan Plateau show a major low in the Bouguer anomaly ($\sim$500 mgals), as expected for a region with thickened crust, and satellite gravity data have been used to infer crustal thickness variations (Shin et al. 2007). Satellite magnetic data from the Tibetan Plateau have detected a shallow Curie depth which indicates high temperatures and by inference partial melting in the crust (Alsdorf and Nelson 1999).

4.3 MT Studies of the Central Himalaya

Several MT studies have taken place in the central Himalaya as shown in Fig. 4 and listed in Table 1. The rugged terrain and international borders have not allowed the MT stations and profiles to be ideally placed. Profiles published to date include, from West to East, Garwhal Himalaya (Israil et al. 2008), Nepal (Lemmonier et al. 1999) and the Sikkim Himalaya (Patro and Harinarayana 2009). Each of these MT profiles images the unconsolidated sediments of the Indian Foreland as a zone of low resistivity. Active convergence is accommodated on the Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) and the models of Israil et al. (2008) and Patro and Harinarayana (2009) show northward dipping conductors that are probably due to underthrust sedimentary rocks units in the footwalls of these thrust faults. Similar structures were reported by Gokarn et al. (2002b) in the Siwilak Himalaya. Higher resistivities are observed where higher grade metamorphic and igneous rocks are mapped to the North. On all three profiles a conductor has been observed close to the location where the MHT steepens to the North. The results in Nepal and Gharwhal show that this conductor is spatially coincident with a zone of significant seismic activity at a depth of 10–20 km and it has been speculated that this may be related to the presence of crustal fluids (Lemmonier et al. 1999).

4.4 MT Studies of Southern Tibet

The geoelectric structure of Southern Tibet was first investigated by the Sino-French MT studies (Yuan et al. 1985). Since 1995 the geoelectric structure of this region has been further investigated by the INDEPTH project with a combination of broadband MT (period range 0.01–1,000 s) and long-period MT (period range 10–10,000 s) on three profiles extending from 85°E to 95°E (Chen et al. 1996; Unsworth et al. 2005; Spratt et al., 2005; Ye et al. 2007). These profiles have confirmed the presence of the mid-crustal conductor

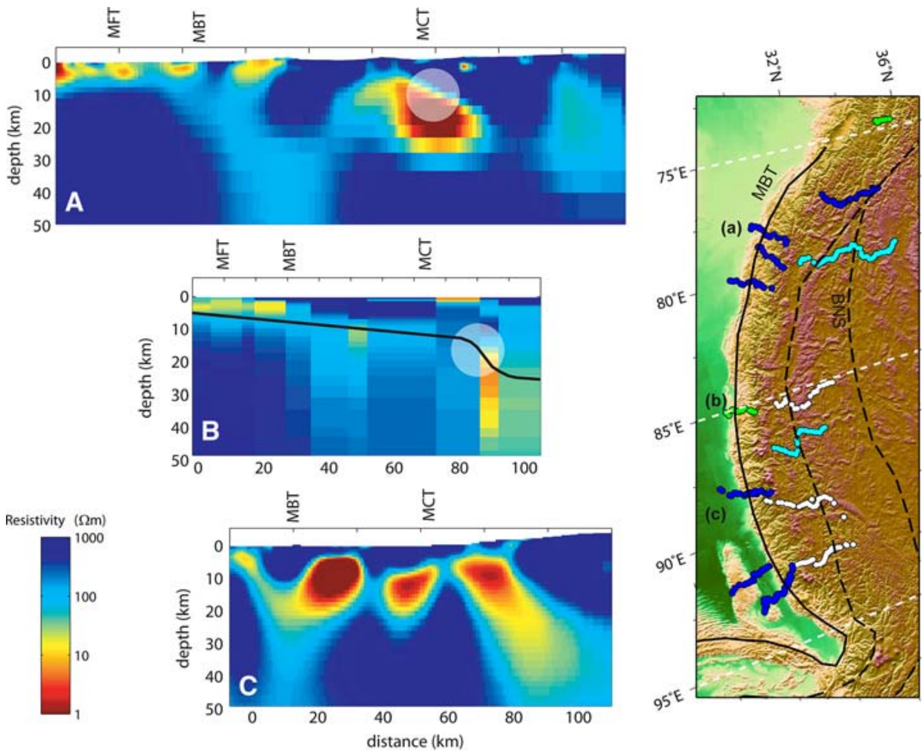

Fig. 4 Detailed map of Himalaya showing MT profiles of **a** Israil et al. (2008), **b** Lemmonier et al. (1999) and **c** Patro and Harinaranya (2009). The *white circle* in models (**a**) and (**b**) are clusters of seismicity. *MBT* Main Boundary Thrust, *MFT* Main Frontal Thrust, *MCT* Main Central Thrust. *Black line* in (**b**) shows top of underthrusting Indian Plate

that was detected by previous Sino-French studies and have defined its areal extent and geometry. The southern edge of the conductor is located South of the ITS in the Tethyan Himalaya on the INDEPTH 100, 700 and 800 lines (Figs. 3, 5). The top of the conductor appears to be coincident with a negative polarity seismic reflection (Brown et al. 1996) giving additional support to the idea that the mid-crust has an elevated fluid content. However, MT alone cannot determine the nature of the fluid (Li et al. 2003). Seismic reflection data have been used to determine if the amplitude versus offset (AVO) characteristics can determine if the fluid is aqueous or partial melt (Makovsky and Klemperer 1999). In this type of analysis, the reflection coefficient is measured at a range of angles of incidence. Given the elevated temperatures and anticipated high fluid content in Southern Tibet, it is likely that temperatures are high enough for partial melting to occur. The initial INDEPTH 100-line described by Chen et al. (1996) was located at 90°E within the Yadong-Gulu rift (Armijo et al. 1986) and it was speculated that the presence of partial melt could be due to the rift zone. Subsequent MT profiles were collected in 2001 outside these rifts (INDEPTH 700 and 800-lines) and both show broadly similar resistivity structures to the profile within the rift, suggesting that a mid-crustal layer of fluids is a ubiquitous feature of the Himalayan orogen and not solely due to the effect of rifting (Unsworth et al. 2005; Ye et al., 2007). The INDEPTH 200-line profile (Li et al. 2003) crossed the

Table 1 List of MT surveys in the Himalaya and Tibetan Plateau shown in Fig. 3

Location	Label	Group	References
Nanga Parbat	NP	UC Riverside, MIT	Park and Mackie (2000)
NW Indian Himalaya	HIMPROBE	Indian Institute of Geomagnetism	Gokarn et al. (2002a)
NW Indian Himalaya	HIMPROBE	Wadia Institute	Arora et al. (2007)
Garwhal Himalaya	GH	Wadia Institute	–
Garwhal Himalaya	IIT	Indian Institute of Technology, Roorkee	Israil et al. (2008)
Nepal Himalaya	L99	France	Lemmonier et al. (1999)
Sikkim Himalaya	SK	National Geophysical Research Institute	Patro and Harinaranya (2009)
Shillong Plateau	G8	Indian Institute of Geomagnetism	Gokarn et al. (2008)
Eastern Himalaya	IIG	Indian Institute of Geomagnetism	–
Central Tibet	Z96	China University of Geosciences, Wuhan	Zhang et al. (1996)
Southern Tibet	100	INDEPTH	Chen et al. (1996), Unsworth et al. (2005)
Yadong Gulu Rift	200	INDEPTH	Chen et al. (1996), Li et al. (2003)
Southern Tibet	700, 800	INDEPTH	Unsworth et al. (2005), Spratt et al. (2005)
Central Tibet	500	INDEPTH	Wei et al. (2001), Solon et al. (2005)
Northern Tibet	600	INDEPTH	Wei et al. (2001), Unsworth et al. (2004)
Southern Tibet	CUGB	China University of Geosciences, Beijing	Jin et al. (2006), Ye et al. (2007)
Qaidam Basin	CUGB	China University of Geosciences, Beijing	–
Western Tibet	CUGB	China University of Geosciences, Beijing	–
Eastern Tibet	S03	China Earthquake Administration	Sun et al. (2003)
Eastern Tibet	Z08	China Earthquake Administration	Zhao et al. (2008)
EHS	EHS3D	Chinese Academy of Sciences	Bai et al. (2009)
Eastern Tibet	CEA	China Earthquake Administration	–
Eastern Tibet	M05	Chinese Academy of Sciences	Ma et al. (2005)
Tien Shan	B03	UC Riverside	Bielinski et al. (2003)
Qilian Shan	B01	University of Washington	Bedrosian et al. (2001)
Tengchong	TC	Chinese Academy of Sciences	Bai et al. (2001)
Ruili	RL	Chinese Academy of Sciences	Bai et al. (2003)

Damxung Graben (part of the Yadong-Gulu rift system) and showed that low resistivities were not confined to the rift. These observations of low resistivities can be interpreted as implying an elevated fluid content, and have provided support for geodynamic models that invoke crustal flow to explain the structure of the Himalayan orogen (Beaumont et al. 2001). This was quantified by Unsworth et al. (2005) who showed that crustal resistivities observed in Southern Tibet were consistent with a factor of ten reduction in strength in the mid-crust. Other geological observations challenge the view that extensive crustal flow occurs (Kohn 2008) and this debate is reviewed by Klemperer (2006).

4.5 North West Indian Himalaya

The North West Himalaya in India has been studied as part of the HIMPROBE project that included teleseismic receiver function studies (Rai et al. 2006) and MT surveys (Gokarn et al. 2002a; Arora et al. 2007). As in the Central Himalaya, the MT data image a dipping conductor located at the top of the underthrusting Indian Plate (Arora et al. 2007). North of the ITS, the mid-crust has a low resistivity (Gokarn et al. 2002a; Arora et al. 2007) that was explained on the basis of partial melting, although the amount of melt required in the North West Himalaya is less than in Southern Tibet. This observation may be explained if the lower convergence rates in the western Himalaya, compared to the Central Himalaya, have generated smaller amounts of melt through slower crustal thickening. It has also been

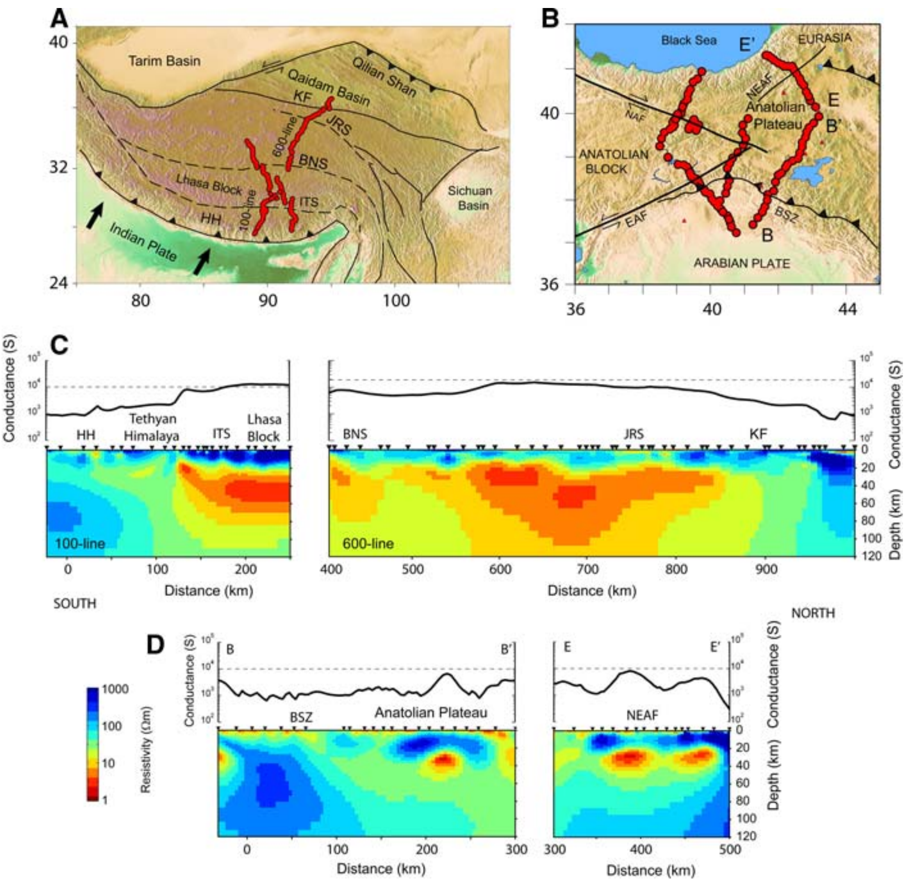

Fig. 5 **a** Location of INDEPTH profiles in Tibet (Unsworth et al. 2004, 2005) and **b** profile location in Eastern Anatolia from Turkoglu et al. (2008). *EAF* East Anatolian Fault; *NAF* North Anatolian Fault; *NEAF* Northeast Anatolian Fault; *BSZ* Bitlis Suture Zone; *QB* Qaidam Basin. Other labels as in Fig. 3. **c** Resistivity models for the 100 and 600 line INDEPTH profiles **d** Resistivity models for MT profiles crossing the Anatolian Plateau. The conductance (conductivity integrated from the surface to 100 km) is also shown

suggested that a southward directed flow channel could have been disrupted by strike-slip motion on the Karakorum Fault (Leech 2008). Geothermal studies in this region have used MT, but have not allowed shallow reservoirs to be related to regional scale conductors (Harinaranya et al. 2004).

4.6 Himalayan Syntaxes

Tectonic processes at the eastern and western ends of the Himalaya are distinct from those occurring in the central Himalaya. At these Himalayan syntaxes there is evidence that rapid uplift is coupled to erosion and deformation and the syntaxes have been described as tectonic aneurisms (Zeitler et al. 2001). An integrated study of the western Himalayan syntaxis at Nanga Parbat showed that a mid-crustal conductor was regionally present in this region, but was absent directly beneath the rapidly uplifting peak of Nanga Parbat (Park and Mackie 2000). The high crustal resistivity was interpreted as being due to the absence of fluids. It is proposed that the rapid deformation maintains a network of fractures that provides an effective mechanism for removing fluids. Broadband MT data have been collected by China University of Geoscience (Beijing) close to eastern Himalaya Syntaxis (Fig. 3) but spatial coverage did not allow the geometry of a regional mid-crustal conductor to be fully determined (Jin et al. 2006).

4.7 Deformation Within the Indian Plate

Crustal deformation in the India–Asia collision zone is relatively asymmetric with most deformation occurring in the Asian plate. However, the Indian plate undergoes faulting towards the eastern end of the Himalaya in the Shillong Plateau. Clark and Bilham (2008) suggest that this type of deformation will ultimately reduce both the deformation rates and elevation in the Himalaya as the zone of deformation becomes broader in a North–South direction. Gokarn et al. (2008) report an MT study of the Shillong Plateau and showed that some major faults proposed from geodetic studies could be identified as dipping zones of low resistivity.

4.8 Regional Scale MT Studies of the Central and Northern Tibetan Plateau

North of the Himalaya, the Tibetan Plateau is characterized by an extensive region of flat high elevation. Several MT surveys have defined the first order resistivity structure of this region of the Tibetan Plateau (Fig. 3). Zhang et al. (1996) describe three broadband MT profiles that extended across the Qiangtang terrane and showed that a mid-crustal conductor was present in the central Tibetan Plateau. Solon et al. (2005) report a more detailed study of the INDEPTH 500-line where it crossed the Bangong-Nuijiang suture (BNS) and showed an increase in the conductivity of the mid-crustal layer to the North. Mechie et al. (2004) used a combined analysis of the 500-line MT data and coincident seismic reflection data to determine the depth of the α-β quartz transition. Wei et al. (2001) showed that the mid-crustal conductor was present beneath the INDEPTH 600-line and extended across the Songpan-Ganze terrane and terminated close to the surface trace of the Kunlun fault at 94°E. North of the Kunlun fault the upper mantle is relatively resistive, indicating that the Kunlun Fault is a major boundary in terms of resistivity, and by implication rheology.

Many geodynamic models make specific predictions about the structure in the lower crust and upper mantle beneath Tibet. The presence of a conductive crustal layer is a problem in this respect, since MT data have reduced sensitivity to geoelectric structure beneath a conductor. Long-period MT data on the Northern Tibetan Plateau were carefully analysed and support the presence of a shallow asthenosphere in this region (Unsworth et al. 2004). Long-period MT data in southern Tibet were collected with the goal of defining upper mantle structure in that region, but the higher mid-crustal conductance and data quality did not permit this (Spratt et al. 2005).

The Tibetan Plateau continues to grow to the North East through active thrusting in the Qilian Shan and ranges to the South (Figs. 3, 5). Strike-slip motion on the Altyn Tagh Fault (ATF) is transferred to these thrust faults causing the ATF to terminate around 98°E (Meyer et al. 1998). Bedrosian et al. (2001) describe commercial MT data collected in this area and showed that MT could image the geometry of the thrust faults which were around 10–15° from the surface to a depth of 4 km.

4.9 Large Scale Crustal Flow in Eastern Tibet

Geodynamic models invoking large scale crustal flow have been successful in explaining the topography, surface velocities and uplift history of the eastern Tibetan Plateau. Royden et al. (1997) described evidence for extensive surface uplift with minimal horizontal shortening. Clark and Royden (2000) explained this observation with crustal flow that is confined to a mid-crustal layer which does not reach the surface. Thus, in regions where the flow terminates, the addition of crustal material causes hydraulic uplift of the surface as the crust is thickened. Clark and Royden (2000) showed that this could account for the steepness of the margins of the Tibetan Plateau. Where crustal flow is impeded by thick lithosphere, the margin was quite steep (e.g. on the western margin of the Sichuan basin in the Longmenshan). In regions where the topography is not steep, lower crustal flow occurs easily and is consistent with a viscosity of 10^{18} Pa s. These calculations have been extended to explain localized dynamic topography (Clark et al. 2005). Copley and McKenzie (2007) used an alternative geodynamic model and showed that the surface velocity was consistent with gravitationally driven flow when the crust has a uniform viscosity of 10^{20} Pa s in Southern Tibet and 10^{22} Pa s in Southeastern Tibet (between EHS and Sichuan Basin).

Geophysical data are needed to validate the crustal flow models that have been proposed. It must be stressed that geophysical imaging can determine the strength and other properties of the crust and mantle. This information can then be used to infer that crustal flow may occur, but does not prove that it actually occurs. Recent teleseismic studies in southeastern Tibet have revealed a spatially extensive low velocity layer at mid-crustal depths, which is consistent with the presence of a weak, fluid rich layer (Yao et al. 2008; Xu et al. 2007). Magnetotelluric data also reveal the presence of a low resistivity layer than can be interpreted as a weak layer. The INDEPTH profile in Northern Tibet crossed a zone of low resistivity that was interpreted by Unsworth et al. (2004) as being an eastward zone of crustal flow. Zhang et al. (1996) also inferred that the low resistivity zone beneath the Qiangtang terrane could be associated with crustal flow of some type. Clark and Royden (2000) predicted that this crustal flow channel is diverted around both sides of the Sichuan basin. An MT survey by Sun et al. (2003) showed that the mid-crustal low resistivity zone terminated on the West side of the Sichuan Basin, as predicted by Clark and Royden (2000). Studies of the Tengchong volcanic area by Bai et al. (2001) showed evidence for localized high conductivity at depth. Other MT profiles have mapped a low resistivity crustal layer that supports the existence of a mid-crustal layer that could be weak enough to flow (Ma et al. 2005; Jin et al. 2006; Zhao et al. 2008; Bai and Meju 2003). Most recently an extensive MT survey in Eastern Tibet has shown that these zones of low resistivity can be traced from profile to profile over a distance of more than 1,000 km (Bai et al. 2009). Estimates of crustal deformation by Allmendinger et al. (2007) also support the outward flow of lower crustal material in Eastern Tibet.

4.10 Tien Shan

In all continent–continent collision zones deformation occurs within the continent at a significant distance from the location of the collision. Regions of deformation can be separated from the locus of collision by regions showing minimal deformation that are hundreds of kilometres wide. This effect is observed in the India–Asia collision into the North of the Tibetan Plateau. Minimal internal deformation occurs within the Tarim Basin, yet a high rate of deformation is observed to the North in the Tien Shan, with some estimates suggesting that 40–50% of the deformation of the entire India–Asia collision is accommodated there (Thompson et al. 2002 and references therein). An important question to be understood is what factors control this spatial distribution of deformation. Bielinski et al. (2003) describe a combined broadband and long-period MT profile that crosses from the Tarim Basin to the Kazakh Platform. The crust in the Tien Shan is 70–80 km thick on the northern and southern margins, yet thins to 50 km in the centre. This study imaged highly variable resistivity in the crust, and showed that the upper mantle beneath the thinned crust was quite resistive (>200 Ωm).

5 Arabia–Eurasia Collision Zone in Eastern Anatolia

5.1 Geological and Geophysical Background

The Arabia–Eurasia collision in Eastern Anatolia is generally accepted to be at a younger stage of development than the India–Asia collision (Dewey et al. 1986; Sandvol et al. 2003) with an onset of collision at around 12 Ma. The relatively young age of this collision gives an opportunity to investigate (1) which features are common to both collision zones and (2) investigate the temporal evolution of collision zones. Other authors suggest that this collision may represent a later stage collision that is in the process of stalling (Edwards and Grasemann 2009).

The present day tectonics are characterized by (a) continued underthrusting of the Arabian Plate along the southern margin of the plateau along the Bitlis suture zone, (b) westward motion of the Anatolian block along the North and East Anatolian fault system and (c) crustal thickening that extends northward into the Caucasus mountains (Reilinger et al. 2006). The regional geology of Eastern Anatolia is characterized by extensive volcanic rocks that range from basaltic intraplate volcanoes on the Arabian Plate to subduction related volcanoes further North on the Eurasian Plate (Pearce et al. 1990). Gravity and passive seismic studies show that the crust beneath the 2 km high plateau has been thickened to around 50 km (Zor et al. 2003). Receiver function studies reveal local low-velocity zones in the crust that have been interpreted as localized partial melting (Angus et al. 2006). Regional shear wave propagation show anomalously low velocities in the upper mantle (Gok et al. 2007) which together with the distribution of volcanoes, and patterns of lava composition support the idea that some type of lithospheric delamination has occurred (Keskin 2007).

5.2 Magnetotelluric Studies of the Arabia–Eurasia Collision

The first regional scale MT study of eastern Anatolia is described by Türkoğlu et al. (2008) and used primarily long period MT data to study large scale resistivity structure on two main transects extending from the Arabian Plate to the Black Sea. The eastern transect (BB' and EE' in Fig. 5) is located where direct convergence occurs between the Arabian and Eurasian plates. The resistivity model obtained by 2D inversion of the data is shown in Fig. 5 and reveals a low resistivity mid-crustal layer. The conductance of this layer locally exceeds 5,000 S, but it does not maintain this value over the same spatial area as observed in Southern Tibet (Fig. 5). The low resistivity pockets in the crust appear to correlate with the locations of seismic low velocity zones defined by receiver functions (Angus et al. 2006). The fact that the crustal conductance in Anatolia is lower than in Southern and Central Tibet has the advantage that the resistivity of the upper mantle can be constrained in Anatolia. The upper mantle in this region has resistivity $\sim$30 Ωm which is typical of values expected for the asthenosphere (Jones 1999; Eaton et al. 2009), providing strong support for geodynamic models that invoke delamination. MT studies in Armenia and Georgia reported by Berdichevsky et al. (1996) showed that low resistivities in the mid-crust extends into the Lesser Caucasus.

5.3 Crustal Flow in Eastern Anatolia

The low resistivity zones beneath the Eastern Anatolian Plateau have a resistivity around 3 Ωm. This observation can be interpreted as implying that the layer is an order of magnitude weaker than the adjacent rock (Unsworth et al. 2005). As in Southern Tibet, geodynamic modelling suggests that this amount of weakening is a required condition for crustal flow (Beaumont et al. 2001). However, the low resistivity crustal zone in Anatolia is not continuous in a North–South direction implying that if crustal flow occurs, it is in the orogen parallel direction (East–West). The western MT profiles of Türkoğlu et al. (2008) cross the Anatolian block where it is being extruded westward, and again the resistivity values are consistent with a weak lower crustal layer. Further West, Anatolia is characterized by high heat flow and extension, and the lower crust is highly conductive (Bayrak and Nalbant 2001). Again it must be stressed that the presence of a conductor implies a relatively weak layer, but it can only be inferred that the layer is actually flowing.

5.4 Intracontinental Deformation in the Arabia–Eurasia Collision Zone

The analogous feature to the Tien Shan in the Arabia–Eurasia collision is the 5,000 m high Caucasus mountain range (Philip et al. 1989). The Caucasus represents the northern extent of deformation and is separated from the Anatolian Plateau by a relatively narrow zone of lower elevations in Armenia and Georgia. No deep sounding MT studies have been reported from this region.

6 European Alps and Pyreenes

The European Alps are one of the most studied mountain belts on Earth. Over the last 100 years detailed mapping has taken place and given evidence for many important geological processes in orogenic belts. Observations in the Alps led Argand (1924) to formulate his ideas of ductile deformation of the crust. The Alps were formed by a collision that closed the Tethys Ocean as the European Plate was subducted southward beneath parts of the African Plate (Apulian and Adriatic). The collision was relatively long-lasting and complex with major events in the Cretaceous and early Tertiary (see syntheses and reviews by Coward and Dietrich 1989; Edwards and Grasemann 2009). The subducting oceanic slab is believed to have detached in the Eocene, and extensive strike-slip motion on major faults has been documented in the Eastern Alps (Robl et al. 2008). Structural mapping and seismic reflection have been combined to image structures from outcrop to the upper mantle, and are dominated by South-dipping structures in the crust formed by underthrusting (Schmid et al. 1996). Geodetic data show relatively slow rates of deformation across the Alps of the order of 2 mm per year (Caporali et al. 2008), which is more than an order of magnitude less than for convergence across the Himalaya. It appears that the Alps are in a late stage of collision with gravitational collapse occurring in the West and horizontal extrusion continuing in the East (Selverstone 2005). A localized MT survey in the Pennine Alps of Switzerland by Losito et al. (2001) showed that zones of high conductivity were caused by the presence of interconnected graphite. No regional scale MT transects of the Alps have been published, partly because of the high electromagnetic noise levels from electric railways and hydroelectric power stations.

The Pyrenees are part of the Alpine orogeny and are the result of the collision between Iberia and Europe from the Late Cretaceous to early Miocene. Seismic studies suggest that Iberia has underthrust Europe more than 100 km (Dagnieres et al. 1989). MT surveys have revealed a major zone of crustal high conductivity (Pous et al. 1995; Ledo et al. 2000) that has been interpreted as a zone with at least 5% partial melting (Glover et al. 2000).

7 Altiplano-Puna Plateau

The Altiplano-Puna Plateau in the Central Andes is 1,800 km long and 300–400 km wide, making this the second largest plateau on Earth. In contrast to the Tibetan and Anatolian Plateaus the Altiplano-Puna Plateau has been uplifted without terrane accretion or continent–continent collision. Although not a true continent–continent collision, studies of this feature are relevant to this review because they show that two quite different sets of tectonic processes can both result in the formation of a high plateau (Allmendinger et al. 1997). Uplift has occurred by horizontal shortening on both the eastern and western margins (Elger et al. 2005) and is driven by mechanical coupling between the subducting Nazca Plate and the overriding South American Plate. The effect of this East–West compression has been amplified by mechanical weakening of the Andean crust (Allmendinger et al. 1997; Sobolev and Babeyko 2005). Subduction has occurred here for more than 200 Ma, yet uplift of the Altiplano-Puna only began 25 Ma, perhaps due to an increase in the plate convergence rate at that time. In contrast to the Tibetan Plateau, the Altiplano-Puna exhibits abundant volcanism. Long-period MT surveys by Brasse et al. (2002) at 21°S and Schwarz and Kruger (1997) at 22°S showed that the southern Altiplano has a very high crustal conductivity, with the conductance locally exceeding 20,000°S (Fig. 6). This has been interpreted with melt fractions in excess of 14%. Schwalenberg et al. (2002) undertook a sensitivity analysis of this model and showed that the base of the conductor could not be detected with the MT data. This conductor is not a universal feature of the Altiplano as it is not present further North near 18°S (Brasse and Eydam 2008).

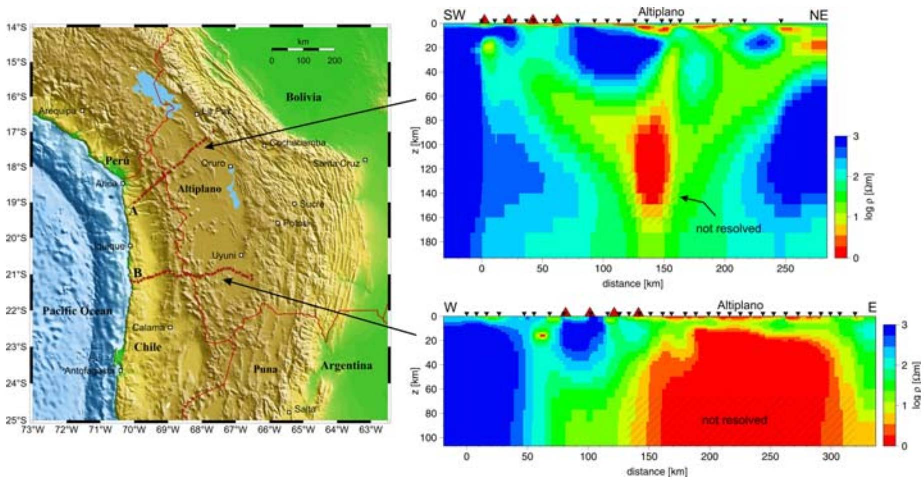

Fig. 6 Resistivity models derived from 2D inversion of MT data collected on the Altiplano; *lower panel* is from Brasse et al. (2002) and *upper panel* shows Brasse and Eydam (2008). *Red triangles* show the volcanic arc

8 Summary and Conclusions

The MT studies of collision zones described in this paper are important for two reasons. Firstly they can show what tectonic features and processes are typical of all collision zones and which are orogen specific and dependent on starting conditions. Sengor and Kidd (1979) noted the similarities between the Tibetan Plateau and the Anatolian Plateau, both in terms of active tectonics and seismic velocity structure. In neither orogen does the colliding plate underthrust the entire plateau and both are characterized by zones with a shallow asthenosphere. These similarities are also obvious in the MT studies reviewed in this paper. Froidevaux and Ricard (1987) compared the Tibetan Plateau to the Altiplano and noted that both showed similar patterns of thrusting at low levels and extension at higher elevation.

A second reason why comparative studies of multiple collisions are useful is that they can also give insight into the temporal evolution of collision zones. For example, it has been recognized that the Arabia–Eurasia collision zone is at an earlier stage of temporal evolution than the India–Asia collision in Tibet (Dewey et al. 1986). Thus it is possible, at least in principle, to elucidate some first order features about the temporal evolution. However, if an objective comparison is to be made, then sufficient data must be gathered to fully understand variations in starting conditions. The Eastern Turkey Seismic Experiment was a step in this direction since it attempted to collect a comparable dataset to that already gathered in Tibet (Sandvol et al. 2003).

Future magnetotelluric studies of active collision zones have the potential to provide new constraints on the rheological properties of the crust and upper mantle. As this type of analysis is further developed, it must take into account the non-uniqueness inherent in (a) converting geophysical data into a model of subsurface resistivity and (b) interpreting this resistivity in terms of composition. Despite the limits imposed by this non-uniqueness, it is clear that, in many collisional orogens, a widespread zone of low resistivity is observed in the crust. It is significant that this appears to develop for a wide range of tectonic histories and settings. As in many areas of geodynamics, a number of important questions remain unanswered. In many of the study areas described in this review, the coverage of MT stations is inadequate to define the resistivity structure with confidence in 2D, yet alone 3D. Mapping possible flow channels will require a detailed grid of MT stations, with consistent high quality MT data recorded at each. Acquisition of this type of dataset might also provide enough coverage to determine if electrical anisotropy is associated with flow and deformation in these zones. Future high resolution MT surveys will need to be implemented as part of multidisciplinary studies to provide the most reliable images of subsurface structure.

Additional research is still needed to determine the relationship between the composition of lower crustal and upper mantle rocks and their strength over geological time-scales. The question of why the lower continental crust is so often low in resistivity in stable regions is relevant to studies of active deformation, since active regions will evolve over time into regions that are stable.

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