Global Tectonics: Do Concepts, Observations and Problems Merge toward a New Paradigm?

Abhijit Deonath
Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia
Email: adeonath@gmail.com

Abstract: For decades, plate tectonics has revolutionised the philosophy behind almost all aspects of the Earth sciences. It provided right platform for advancement of diverse geoscientific fields. However, its assumptions, limitations and overstretching are increasingly pointing toward its inadequacies, particularly in recent times when a wealth of accurate data is being gathered. A need for a different outlook is felt among many geoscientists. Here it is shown that high-level analyses of various diverse topics of Earth science merge towards an alternative paradigm which draws a lot from the plate tectonic theory but still has substantial fundamental differences. The proposed paradigm considers most tectonic activities to be centred around two types of linear features on Earth's surface – active continental margins and rifts both dynamically linked with one another. It envisages that the old oceanic lithosphere at the active continental margin manifests sinking tendency and the resulting pull drives continental uplift, rift and breakup. The oceanic lithosphere itself develops broad folds which are amplified as the ridge-push forces are transferred as compression at the margin. This results in a series of activities at the margin which is responsible for many rock types, geological events and growth of continental crust. The paradigm is proposed in the light of a variety of concepts, observations and problems of geology which it attempts to merge together and address. The proposed paradigm can stimulate healthy debate among scientific community which is necessary for further advancement of Earth sciences.

Keywords: Global tectonics, plate tectonic theory, concepts, observations and problems, alternative paradigm

Introduction

Plate tectonics has been successful in explaining many global-scale Earth features and has influenced many disciplines of the Earth and allied sciences. The theory has inspired several associated concepts and conundrums like subduction factory, mantle plumes, slab rollback, tectonic mode switches, channel-flow within crust, exhumation of ultrahigh pressure (UHP) metamorphic rocks, accretion of "suspect" terrains, ridge subduction, petrogenesis of various basalt types, occurrence of paired metamorphic belts and ophiolites, and association of hydrothermal deposits with arc magmas, to name a few. The plate tectonic theory has, at the same time, suffered from many assumptions such as the plates are rigid and that the mantle is homogeneous (Anderson, 2006); and overstretching such as invocation of multiple subduction zones to explain certain orogenies (e.g., Coney, 1992) and postulation of many small plates such as the Burma microplate (Curray et al., 1979). There are problems associated with explaining the entire mechanism of plate tectonics. Questions that are still unanswered include: what drives the plate motion, how subduction is initiated, what causes the distinction between slow- and fast-spreading ridges, what is the reference frame of plate motion, and so on. With great deal of data accumulating from modern techniques encompassing deeper Earth, oceans and skies, observations are sometimes found to be difficult to reconcile with the conventional plate tectonic theory. For example, the notion of narrow plate boundaries, a fundamental tenet of plate tectonics, has been challenged when broad deformation zone in central Indian Ocean was discovered (Royer and Gordon, 1997). Some classical problems of geology such as origin of granite and anorthosite and granite "room problem" are yet to be resolved to the satisfaction of the majority. A few other problems have surfaced in recent times like origin of supra-subduction zone ophiolites, formation of the Tibetan Plateau and exhumation of high-pressure diamond and coesite-bearing metamorphic rocks. This paper takes a multidisciplinary approach by applying cognitive operation on data and views on diverse topics associated with global tectonics to arrive at a generic paradigm. The approach is similar to mental processing of stereoscopic images which individually don't show the other dimension, but when focused together, initially appear blurry until the depth dimension becomes apparent and a clear picture emerges. The main points of the proposed paradigm are:

1. Upon ageing, an old oceanic lithosphere along a continental margin begins to sink.
2. The pull because of the sinking tendency causes uplift of the continent at a weak zone and development of broad folds at the margin.
3. Continental uplift results in decoupling of subcrustal layers and associated continental magmatism followed by breakup and seafloor spreading.
(4) Ridge push due to spreading translates into compressive forces at the active margin on the opposite side of the continent. The folds are amplified because of the compressive forces.

(5) At the active margin, fold amplification causes decoupling of subcrustal layers, development of axial plane fractures and entry of seawater into subcrustal space.

(6) The subcrustal space under the crest of the amplified fold is the main factory for production of a suite of magmatic rocks with water acting as the change agent.

(7) Granitic rocks formed under the bulge are accreted to the continent under the influence of continuing compressive regime which also leads to formation of high-pressure metamorphic rocks.

**Global-scale Concepts, Observations and Problems**

Some recent advances in topics of geology that have global significance are analysed below. Individual topics by themselves may initially appear to be random and fuzzy until the outcomes of the analyses are synthesised further.

**Structure and Behaviour of Lithosphere**

Seismic tomography diagrams have of late become popular among geoscientists. Their usefulness in understanding the structure of interior is indisputable, particularly with high-resolution images. Their interpretation in three dimensions however remains a very challenging task due to many unresolved issues, for example, lack of sufficient analyses of depth resolution of images and poor understanding of sensitivity of seismic velocity to changes in composition, temperature and pressure (Trampert, 1998). Adding the time dimension makes it more complicated. Most tomographic studies are selective, zooming in at subduction zones or the so-called hotspots (Zhao, 2004; Fukao et al., 2001). One clear view from global seismic tomography (Zhao, 2004) is that the velocity zones at various depths follow patterns that appear to be governed by surface positions of continents, continental margins and mid-ocean ridges (MOR). Up to shallow depths (~600 km) fast velocity zones underlie the continents and rise up as a band underneath the subduction zones to represent oceanic lithosphere. Slow velocity zones on the other hand are found at shallow depths around mid-ocean ridges and above the fast band at subduction zones.

The rheology of oceanic lithosphere varies continuously as it moves away from the MOR and cools with age (Strüve, 2002). A significant consequence of ageing is increase in the thickness of the lithosphere by transformation of asthenospheric mantle to lithospheric mantle so much so that it becomes ~100- km thick in about 80 million years (Cloos, 1993). Another obvious effect of cooling is increase in density of oceanic lithosphere. Thus with increasing distance from the MOR, the density difference between the lithosphere and the asthenosphere gradually decreases. A density difference of approximately less than 10% will make the lithosphere tend to sink into the asthenosphere (Schott and Schmeling, 1998; Schott et al., 2000; Meissner and Mooney, 1998; Anderson, 2006). Gradual increase in density of oceanic lithosphere, at one stage, reaches this point when it starts sinking into the mantle causing pull, which is of the order of 10^13 Nm^-1 (Turcotte and Schubert, 1982). Oxburgh and Parmentier (1977) indicate that gravitational instability of oceanic lithosphere commences when it is ~40 million years old. Why do we then still see oceanic crust as old as Jurassic at the surface? What stopped them from being dragged down at least 100 million years ago?

Theoretical calculations of strength and strain rate of lithosphere indicate oceanic crust is significantly stronger than continental crust (Strüve, 2002). This can be seen from simple strength calculations considering quartz as representing continental crust and olivine representing oceanic crust. Further, rocks are weaker in extension than in compression (Anderson, 2006).

The two fundamental responses of lithosphere to stress are: folding because of compression and normal faulting due to extension. Burg and Podladchikov’s (2000) numerical modelling of lithosphere under far-field compression with physical conditions representing the Himalayan syntaxes has demonstrated crustal folding as a basic response to shortening. Their model further concluded that a cold crust (as is the case with marginal oceanic crust) buckles with higher amplitude and wavelength than a hot one and that shortening beyond about 25% causes decoupling between lithospheric layers. Numerous continental fluvial basins serve as examples of normal faulting under extension. Tension in the upper parts of the oceanic crust during bending is also known to cause normal faulting parallel or sub-parallel to the trench (Masson, 1991; Kobayashi et al., 1998; Grevemeyer et al., 2005).

**Uplift-Glaciation-Breakup-Orogeny Relationship**

The observed synchronicity between major tectonic and magmatic events on a global scale is noteworthy. A strong correlation has been observed between timing of Atlantic separation of North America in late Jurassic and South America in late Cretaceous and of orogenies of American Cordilleras (Coney, 1992). Red Sea formation has been attributed to compression in the Zagros region (Ghebreab, 1998). Eyles and Januszczak (2004) associate Neoproterozoic glaciation with uplift and megairfting related to opening of paleo-Pacific and Iapetus oceans. The Cretaceous Sepik Association of Papua
New Guinea represents a volcanic arc (Brown et al., 1980) which can be correlated with ~125-Ma separation of Australia from Antarctica (Stagg and Willcox, 1992) and eruption of Ontong Java Plateau at ~120 Ma (Korenaga, 2005).

Intraplate Stress and Ocean Plateaus/Islands

Intraplate magmatism is the main reason behind the theorisation of mantle plume concept as a complementary idea to plate tectonics. The theory has since been extended to account for not only all ocean 'hotspots' on the planet, but also other forms of intraplate magmatic and tectonic activities such as flood volcanism and continental rift systems. Looking from a different perspective, parallelism of Pacific volcanic chains with American west coast, Japan-Kurile trench system and northern and eastern margins of Australia may not just be coincidental. It may reflect some relationship with stress induced by marginal forces. South-central Pacific volcanic chains violate the square root law of increase of lithosphere thickness with age and elastic thickness there is much less than the surroundings indicating a regional anomaly (Calmant and Cazevnave, 1987). Besides the central Indian Ocean deformation zone (Royer and Gordon, 1997), the lithosphere under the Rhine graben which is substantially weaker than the surrounding regions (Cloetingh et al., 2006) is an example of intraplate continental stress. The weak zone runs parallel to the coast line of the France or the western coast of the continent of Europe in general.

Basalt Geochemistry

Geochemical signatures of various basalt types and their significance in basalt petrogenesis have been matters of intense study and debate. Ocean-island basalts (OIB) show exceptional enrichment in fluid-insoluble Nb-Ta relative to light rare earth elements (LREE) and large ion lithophile elements (LILE). Strong depletion of Nb-Ta in subduction-related magmas and continental crust is believed to be imparted during subduction processes (Weaver, 1991).

In general, OIBs are enriched in low ionic potential (=valency/ionic radius) trace elements like Cs, Rb, K, Ba, Pb and Sr (LILE) relative to MOR basalts (MORB). It is worth noting that arc magmas are particularly enriched in LILE. These elements are incompatible and water-soluble. Trace elements with high ionic potential (Th, U, Ce, Zr, Hf, Nb, Ta and Ti) occur in high concentrations in OIB relative to MORB though their concentration is low relative to trace elements with low ionic potential. These high field strength elements (HFSE) are incompatible but water-insoluble. OIB has overall high abundance of incompatible trace elements. It is assumed that MORB undergoes hydrothermal alteration with addition of LILE as it moves away from the spreading ridge (Weaver, 1991).

In island-arc basalts and other arc magmas water-soluble LILE (e.g., Pb, Sr, K) are found in abundance, whereas there is marked depletion in water-insoluble HFSE because of relative enrichment in LILE.

Continental Rift-related Magmatism and Tectonic Pulsations

Continental flood basalts (CFB) are widely recognised to be related to continental breakup which initiates as rift basins in the upper continental crust. Rift basins are weak zones in the continental crust that exhibit tectonic pulsations comprising opening and closure of basins. This is evident from occurrence of rifted basins hosting coal formations in regions dominated by gneissic/granulitic rocks (e.g. Damodar Valley coalfields of India) and the complex geology and structure of high-grade terranes (e.g., Arunta Complex of Australia). These linear continental regions often show overprinting of ages as the same region is reactivated because of later tectonic regimes producing Wilson cycle. While it is generally accepted that alkaline rocks and carbonatites occur at places that underwent continental rifting, Burke et al. (2003) hypothesised that deformed alkaline rocks and carbonatites at the same spots represent the collision phase of Wilson cycle.

Association of anorthosite-mangerite-charnockite-granite magmatism with Mesoproterozoic fragmentation of Columbia supercontinent (Zhao et al., 2004) and of rapakivi igneous activity with rapid erosion, crustal thinning and sub-isothermal decompression (Puura and Floden, 1999; Eklund and Shebanov, 1999) are likely pointers to incipient continental rifting. Characteristics of anorthosite massifs, such as general sparsity outside the Proterozoic, typical mineralogy, common association with gabbroic and granitic rocks and invasion of high-grade granulitic rocks, imply that they form initially as plagioclase-rich suspensions in deep-seated chambers and are later intruded into upper levels (Longhi, 2005). Some workers suggest ponding of basaltic magma generated by extension at the base of thickened crust as a likely environment of formation of anorthosites (Mukherjee and Das, 2002).

Marginal/Arc Magmatism

Magmatism at active continental margins and volcanic arcs is believed to be responsible for crustal growth and the role of water in arc magmatism is generally agreed upon. Most workers also acknowledge that dehydration of hydrated mantle is the source of water in the mantle wedge. A study of D and O18 content of water discharged from andesitic volcanoes around Pacific Ocean has shown that most 'andesitic' waters are recycled seawater and so are other volatiles (Giggenbach, 1992). Moreover, because of increase in ion solubility with
pressure, subduction zone water is charged with ions up to 2-3 times the salinity of seawater (Manning, 2004).

Arc magmatism comprising mafic and felsic plutonism and volcanism is reflected in the slow velocity zones above the fast band of subduction zone in seismic tomographic images. Southeastern Australia presents a natural exhibition of the terrains and accretionary processes that lead to growth of continents along its edges. The ubiquitous Cambrian greenstones in temporarily diverse Adelaide Fold Belt, Lachlan Fold Belt and New England Fold Belt (Collins and Vernon, 1994) represent marginal paleo-Pacific oceanic crust adjacent to Gondwanaland prior to tectonic activity.

Hydrothermal deposits around regions of compression tectonism are related to late-stage calc-alkaline magmatism forming shallow plutons (Neubauer et al., 2005). In an interesting study of giant gold deposits, Bierlein et al. (2006) found that deposits form preferably in greenstone belts where the oceanic crust had a short (~70 million years) pre-mineralisation history. Mafic to ultramafic intrusions of asthenospheric origin have been found along near-vertical faults close to these deposits.

**Granite ‘Room Problem’**

The issue of making room for giant granitic batholiths has been one of the outstanding classical problems of geology. Observations from floors of some granitic batholiths such as rapakivi granite of southern Greenland (Hutton et al., 1990) and of unusual style of emplacement of granitic plutons have started to trickle in. The floor of the Bergell pluton in Switzerland appears to have undergone folding at the same time as the upper part of the pluton was undergoing ballooning during syn-magmatic shortening (Rosenberg et al., 1995). Roig and Faure (1998) report laccolith shape of Tulle anticline granites of French Central Massif as opposed to inverted tear-shape. There is no evidence of pluton roof uplift because of magma overpressure. Whereas Hutton et al. (1990) and Tikoff and Teyssier (1992) suggest genetic association between extensional faulting and granite emplacement, Paterson and Schmidt (1999) refute such an association as a case of mere common spatial occurrence. There is a general agreement however that majority of granites are syntectonic. Vigneresse (1999) goes a step ahead and rules that deformation not only influences granite emplacement, but granites need deformation to be generated.

**Metamorphism and Orogeny**

Association of pairs of contrasting metamorphic belts and arc granites has been known from many places for decades, particularly along the Pacific margins (Miyashiro, 1961; Landis and Coombs, 1967). A low P/T metamorphic belt lies closer to the continent than the high P/T as is the case with the classic Japanese belts of Ryoke and Sanbagawa (Brown, 2002; Iwamori, 2000). A close relationship between orogeny and concomitant magmatism and formation of granulites has also been long recognised.

Exhumation of high- and ultra high-pressure metamorphic rocks formed at the subduction zone, particularly when they are transformed to eclogite, is enigmatic because these rocks are traditionally associated with the downgoing slab (Jolivet et al., 2005; Austrheim, 1987). To add to the dilemma, it has recently been found that exhumation rate matches the rate of subduction (Baldwin et al., 2004; Rubatto and Hermann, 2001). Evidence of brittle deformation of eclogites associated with granulites and anorthosites of Bergen Arcs, Norway has been reported by Austrheim and Boundy (1994). A global-scale episodocity of deformation and metamorphic events during last 100 million years has been noted by Lister et al. (2001) which they associate with switching of tectonic mode from compression to extension. They also highlight the occurrence of metamorphic mineral growth at the same time when the deformation mode switched from recumbent folding to extensional shear zone development.

It is now widely accepted that ophiolites occur in supra-subduction zone besides along continental suture zones (e.g., Pubellier et al., 2004). What is the significance of the association of ophiolites with underlying high-grade metamorphic sole (Wakabayashi and Dilek, 2003)?

**Channel-flow within Crust**

Seismologic and magnetotelluric studies of the Tibetan Plateau revealed a low-viscosity middle and lower crust in the region. This initial revelation was combined with some physiographic (flat yet high-altitude topography; high relief along eastern margin of the Plateau) and geological facts (southern Himalayan thrust fault systems and normal-sense displacement of South Tibetan Detachment) to arrive at the channel-flow hypothesis of deformation control in the Himalayan-Tibetan orogeny. The hypothesis, which seems to be gaining popularity day-by-day, suggests the lower and middle low-viscosity Tibetan crust has migrated southward and eastward following Poiseuille flow and extruded as the Greater Himalayan Sequence. Detailed review of the development of hypothesis can be found in Hodges (2006) and fluid dynamics aspects of the hypothesis are discussed in Godin et al. (2006) and Grujic (2006).

**Synthesis of Outcomes: More Questions**

Table 1 summarises some key outcomes from the analyses of topics discussed above. Outcome 1, derived from seismic tomography, outlines a fundamental distinction between continental and oceanic lithosphere. This distinction demands that continents have a significant role in regulating global
Table 1: Summary of outcomes derived from review of global scale concepts, observation and problems related to global tectonics

<table>
<thead>
<tr>
<th>Topic</th>
<th>Outcomes</th>
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<tbody>
<tr>
<td>Seismic tomography</td>
<td>1. Velocity zones at various depths follow patterns that appear to be governed by surface positions of continents, continental margins and mid-ocean ridges.</td>
</tr>
<tr>
<td>Rheology of lithosphere</td>
<td>2. Transformation of asthenospheric mantle to lithospheric mantle means oceanic lithosphere will tend to sink as it moves away from the mid-ocean ridge with ageing.</td>
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</table>
| Lithosphere modelling                      | 3. Two fundamental responses of lithosphere to stress are folding because of compression and normal faulting due to extension.  
                                           | 4. Excessive shortening can cause decoupling between lithospheric layers.                                                             |
| History of major global events             | 5. Synchronicity between major events such as breakup of continents and magmatism, orogeny and glaciation.                               |
| Intraplate deformation/magmatism           | 6. Deformation/magmatism appears to follow linear trends parallel to continental margin.                                               |
| Basalt geochemistry                        | 7. Island-arc basalts show profound effects of aqueous solutions, whereas OIB show effects of small amount of partial melting in the absence of water. |
| Continental magmatism                      | 8. Association of anorthosites with high-grade granulites; probable formation at the base of thickened crust.                         |
| Arc magmatism                              | 9. Highly charged seawater as a major change agent; hydrothermal deposits are related to late-stage magmatism.                        |
| Granite ‘room problem’                     | 10. The problem of making room for large granitic bodies still remains unresolved though several attempts have been made to relate emplacement with extension.  
                                           | 11. Granite generation and emplacement is closely linked with deformation.                                                              |
| Metamorphism and orogeny                   | 12. In orogenies, a low P/T metamorphic belt lies closer to the continent and a high P/T belt usually lies away from the continent.  
                                           | 13. Formation and exhumation of high-pressure and ultra-high-pressure metamorphic rocks is enigmatic.                                  
                                           | 14. Association of ophiolites with high-pressure metamorphic sole demands explanation.                                                 |
| Channel flow                               | 15. Presence of a low-viscosity layer at mid- to low-crustal level underneath the uplifted Tibetan Plateau.                           |
tectonics. Unlike continental lithosphere, the rheology of oceanic lithosphere is not uniform. The two extremes are the MOR where it is almost fluid and the continental margin where the oceanic lithosphere is relatively thick, rigid and dense as highlighted in Outcome 2. Marginal oceanic lithosphere is therefore likely to behave much differently to the freshly emerging lithosphere at the MOR. Marginal oceanic lithosphere is a main centre of tectonic activity because of its special rheology as well as because it borders the ‘vital’ continent. Outcome 6 further strengthens this view. Continents and marginal oceanic lithosphere are the two material blocks where forces need to be applied to model tectonic processes.

Outcome 3 emphasises the role played by two pillars of Structural Geology – folds and faults – in global tectonics. They are major deformation structures formed in response to compressive and extensional forces operating on a global scale. The phenomenon of continental breakup happening around the same time as other major events, particularly orogenesis on a global scale, as per Outcome 5, stresses the importance of finding a link between the two. Do breakup of continents and consequent seafloor spreading influence orogeny at continental margins? Can Outcome 11, which defines deformation as essential condition for granite generation and emplacement, be related to Outcomes 3, 4 and 5? Uplift of continents and glaciation are coeval with orogenic movement elsewhere. Association of granulites with continental magmatism, as mentioned in Outcome 8, points to such magmas being generated and emplaced due to uplift of continent which may or may not lead to complete breakup. Intra-continental basalts show chemical similarity with ocean-island basalts and both could be genetically related to extensional forces operating in the lithosphere. Basalt geochemistry, outlined in Outcome 7, also highlights the typical characteristics of igneous activity at the continental margin which is heavily influenced by incorporation of fluid. The role of water in marginal-arc magmatism is further reinforced by outcome.

Decoupling of lithosphere layers on application of layer-parallel shortening is underscored in Outcome 4 which, combined with uplift of upper layers, may be of great significance to intra-continental and marginal magmatism given that melting due to adiabatic decompression is now widely accepted. Do we get some clue here to resolve the granite ‘room problem’ (Outcome 10)? Does it make subcrustal flow (Outcome 15) look obvious?

Regional metamorphism and high-pressure metamorphism are closely associated with orogeny with high-pressure metamorphic rocks lying away from the continent (Outcome 12) and occurring along with supra-subduction zone ophiolites (Outcome 14). What does such an association signify and what do ophiolites really represent in the light of our present understanding? If we relate granite formation at the margin with deformation, does it not imply the stress can also, at least in part, cause high-pressure metamorphism? Does a blend of outcomes lead us to a viable explanation of the long-standing issue of exhumation of UHP metamorphic rocks? Overall, do the issues provide clues which tend to complement each other and provide a model toward resolution of puzzles of global tectonics?

Discussion

Scientific theories arrive, gain acceptance and some become obsolete with time. Sometimes a new theory simply expands or broadens the scope of the old theory, while at other times the old theory appears as a special case in the context of the new theory. Whatever its eventual fate, it is the set of perspectives and insights, however, that a new theory brings in with it that is of prime significance to the advancement of science. Do points discussed above lead us to a paradigm which takes us a step further in understanding Earth processes? I discuss below a hypothetical idealized sequence of events (Figs. 4 and 5) in the light of the outcomes summarized earlier, aware that introducing a new paradigm is like portraying a hermeneutic circle to some extent.

Let me consider a continental margin bordered by an old oceanic crust as a starting point. Old oceanic lithosphere is dense compared to a new one formed close to the MOR. Negative buoyancy acquired by a fall in density difference between lithosphere and asthenosphere makes the lithosphere subductible when it is ~40 million years old as discussed above. The oceanic lithosphere may still not sink if it is tightly welded to the continental lithosphere. Sinking begins when the combined buoyancy of oceanic lithosphere and the adjacent continent is overcome aided by a pre-existing weak zone in the continent. If the assumption of a tightly coupled continent is held, the sinking of oceanic lithosphere is likely to cause tilt of the continent and subsequent uplift at a weak zone such as the present Rhine graben (Fig. 1). If there is no such weak zone or one cannot be created by the pull, the entire continental mass comes into play. Australia is reported to have undergone tilting during Cretaceous causing maximum sealevel rise and flooding (Gurnis et al., 1998) around the same time as it separated from Antarctica. The sealevel fluctuated thereafter probably reflecting the settling down process of an uplifted continent as it was rifted and carried away northward. More recently, during Neogene the Australian continent tilted substantially with its northern margin going down approximately 250-300 m relative to SSW margin (Sandiford, 2007) probably under the influence of pull at the northern and northeastern margins. Sealevel of age greater than 125 Ma occurs in the western Pacific, northern Atlantic margins of North America and northern Africa and eastern margin of Africa besides some other places (Fig. 2; Royer et al., 1992). Of these margins, only the western Pacific margin is considered as undergoing active subduction. The old
eastern margin of Africa only recently tilted the continental interior parallel to the margin causing the East African Rift, whereas the old Atlantic margins are still to overcome the might of the huge adjoining continental landmasses. That the eastern European continental lithosphere is strong (Cloetingh et al., 2005) implies that the old west Pacific marginal pull to the north of Japan needs to overcome a large buoyancy to begin sinking. It is showing some sinking tendency causing uplift at the Baikal rift with the rift zone running parallel to the margin. Similarly, the old Atlantic oceanic lithosphere at the European continental margin may be causing extension at the Rhine graben.

Figure 2 shows rifted regions (A', B', B'', C', D', E', F', G') and their corresponding sinking margins (A, B, C, D, E, F, G) superimposed on the combined stress map (Reinecker et al., 2005) and isochron map (Müller et al., 1997) of the world. Each such pair exhibits general parallelism. The Andean orogeny has 2 corresponding rifted regions – the southern Mid-Atlantic Ridge and the East Pacific Rise – one reflecting continental breakup and the other showing rifting of oceanic lithosphere. The common scenario is linear marginal sinking causing linear doming of continental interior which often leads to rifting.

Continental weak zones are linear features along which earlier suturing had taken place rendering the regions heavily faulted or regions where earlier aborted rifts had caused thinning of the crust. Highly deformed and metamorphosed granulitic terranes characterize the former and shallow marine to continental sedimentary basins the latter. Continental doming and fracturing is akin to deformation of a wooden slab hinged at the centre with one end fixed and the other end loaded. The inner layers of the slab bend while the outer ones crack at the hinge and the cracks go deeper with time (Fig. 1). The newly created subcrustal space as a result of bending of the continental crust and decoupling causes pressure release for underlying mantle material which begins to melt. The melt is reflected in geophysical signature as observed underneath the Tibetan Plateau (Hodges, 2006) which formed one of the bases of subcrustal channel-flow hypothesis. It is suggested that major faults with high magnitude of slip can propagate downwards up to a depth where a material that allows viscous creep is encountered which prevents stress build-up and hence further fracturing (Handy and Brun, 2004). A fault thus may extend right up to a depth where it encounters a plastic layer in the ductile zone. This is most likely to be in the upper mantle. This could also happen at a higher level in the crust where an earlier body of viscous melt was accumulated in a chamber created by a previous uplift.

The brittle failure of upper crust results in formation of intra-continental basins. The fault-bounded basins get filled up
with sediments carried by water. Water infiltration underground and growth of faults downward go hand in hand. Water has the capability to cause build-up of pore fluid pressure in cracks which, under the influence of tectonic stress field, leads to growth of the faults downward. As the water arrives in the zone of decompression, it aids in melt generation by lowering solidus of mantle material. It also facilitates plumbing of magma upward. Fluid component enables the melt to flow easily. A rising magma interacts with descending water as soon as it leaves the initial magma chamber. Mixing of water at a point along the path lowers the freezing point of the magma preventing its solidification by cooling at that point. This effect may be repeated in wet conditions as magma keeps rising up the conduit causing runaway lowering of freezing point of magma which eventually solidifies at or close to the surface. Thus plumbing aided by water transports the melt to higher levels. Coal formations, which indicate wet surface conditions, are therefore seen interlaced with mafic dykes and sills.

Alternatively, the melt is ponded midway if it cannot be transported all the way up because of lack of sufficient fractures or of water or both. ponding of basaltic melt beneath continental crust provides ideal environment for fractional crystallization of plagioclase forming cumulates. This explains frequent occurrence of anorthosite massifs and lenses in granulite country rocks. Their formation depth corresponding to 10-13 kbar as opposed to emplacement depth of 3-6 kbar is probably a consequence of gradual lifting after formation to higher levels as the continental doming and cracking continues. Initial uplift that produces melt by decompression is not aided by water because of lack of active fractures. Fractures are likely to develop or become activated later causing water entry and plumbing of plagioclase suspension and melt which differentiates to more felsic types which are commonly seen associated with anorthosites.

Extensive cracking of the continental crust provides conduits for outpouring of the melt on to the surface. If parental material of the melt is the residue left after segregation of anorthosite fraction, the resulting CFB shows some negative Eu anomaly the degree of which depends on the amount of plagioclase initially separated (expected to be much less compared to volume of flood basalt). Crustal contamination signature of the CFB is probably imparted by the water that passes through continental crust as it arrives at the magma reservoir leaching ions on its way which are incorporated in the melt.

A geologically recent example of continental tilt is the
westward tilt of eastern Queyras and accompanying doming of Dora-Maira massif of Western Alps during Neogene (Tricart et al., 2004). Similarly, tilt of Saurashtra block in western India during Jurassic-Cretaceous (Biswas and Deshpande, 1983) followed by Deccan volcanism can be related to negative buoyancy at the then northwestern margin represented in exposures now by western ophiolite belt of Pakistan (Gnos et al., 1997). Evidences of dynamic nature of the continental crust-mantle or lithosphere-asthenosphere boundary include an inferred change in vertical modelled rheology between Tibet and Yunnan from coupled to decoupled crust-mantle (Flesch et al., 2005) and thinning of crust and/or updoming of Moho beneath the Rhine graben (Brun, et al., 1991; Mayer et al., 1997; Cloetingh et al., 2006), East African Rift (Sacks and Snoke, 1984; Zoback, 1992), Western Cordillera and Baikal Rift (Zoback, 1992).

The ultimate consequence of the intracontinental uplift and rifting is breakup of the continent and seafloor spreading along the earlier weak zone if the pull at the margin has not died. Spreading is accompanied by transformation of asthenospheric material into lithosphere and generation of new seafloor along the MOR.

Now let us focus on the continental margin where negative buoyancy of the oceanic lithosphere initiated the sinking tendency (Fig. 3). Dissipative forces resist the negative buoyancy (Anderson, 2002) and deformation of crust is one such dissipative force. I propose that instead of subducting, the oceanic lithosphere at the active margin develops broad folds. Uplift of continent and folding of marginal oceanic lithosphere checks the downward pull at the margin thereby preventing the slab from completely sinking (subducting) into the mantle. Furthermore, this margin experiences a boost in compressive forces as the ridge push due to spreading following continental breakup is transferred to this region because the stable continental mass is too rigid to yield to horizontal stress. It is pertinent to remember at this point that the breakup had occurred at the first weak zone thereby leaving no weak zone in the continental fragment which is pushing toward the sinking margin. The compression amplifies the earlier broad folds with profound consequences on the behaviour of the margin as described below (Fig. 4). The trough of the broad warp adjacent to the continent becomes a depocentre for sediment eroded from bulge close to the continent and from continent. The rate of erosion increases with amplification of the fold. When subjected to lateral compression, the oceanic lithosphere is decoupled from the more plastic ultramafic layer below. Decoupling is achieved after the ridge push has been established and further push lifts the upper skin creating space.

**Fig. 3.** Schematic diagram showing fold development at the active margin in three stages (shades same as for Fig. 1). (A) Cooling and ageing of marginal oceanic lithosphere away from MOR (not shown); (B) Development of broad fold at the margin, and (C) Fold amplification because of ridge push (left arrow) causing decoupling of subcrustal layers, faulting at axial planes (f) and entry of seawater into subcrustal space.
The buckling of lithospheric layer creates space under crests and causes high pressure at inflexion points. Increased pressure leads to blueschist-eclogite-facies metamorphism at the limbs of major folds which experience maximum lateral compression. Major faulting occurs at axial planes of the folds. Ranero et al. (2003) used multibeam bathymetry and multichannel seismic reflection images of trench offshore Nicaragua to conclude that active faulting penetrates at least...
20 km deep and that faults are effective conduits for seawater infiltration into crust and mantle at convergent margins. The faults carry seawater to mantle depths, which aid partial melting and also decoupling by lubrication. Majority of melt generated moves further toward the continent under gravity/pressure gradient. The melt is sucked in as the fold amplifies because of continual ridge push thus providing the space required for the granitic melt to evolve and solidify. Migrated melt gets ponded in the space beneath the bulge of the lithospheric layer close to the continent where it further aids in melting initiated by decompression.

Ponding of the basaltic melt close to the continent over a considerable geological period allows differentiation and formation of granite. To use the analogy of a pressure cooker, while granite is being "cooked", excess pressure inside the chamber is released in the form of intermittent volcanism through conduits along the volcanic arc. With continuing push from the ridge the new formed granitic crust is sutured to the continent. During accretion, heat from the cooling granite body combined with compressive forces lead to regional metamorphism/granulite formation along the suture zone.

High amplitudes of fold troughs create ideal depression for deep-sea sediment deposition. Association of widespread turbidite sequence with orogenies (e.g., Lachlan Fold Belt, southeastern Australia) is a testimony to this mechanism. At the same time, amplified bulges are ideal location for fluid-saturated basaltic melts to pond and evolve to granitoid arc rocks. The granitoids cool as shortening continues. The heat released can be utilised in two ways: melting of near-surface rocks to produce further granitoids with crustal signature; and high-T metamorphism with or without accompanying compression. Once the newly formed batholiths are accreted to the old continent, any further melt production and emplacement interior to the new margin is influenced by crustal contamination forming peraluminous (S-type) granites. Compression at the folded margin eventually stops when the ridge-push dies away. A phase of relaxation sets in along the erstwhile folded margin and the resulting melt produced has both mantle and crustal signatures.

Island-arc basalts and other arc magmas show profound effects of water incorporation in the melt. This is reflected in the chemical signatures of the rocks formed at the folded margin. Crystallisation of hydrous magma is accompanied by release of mechanical energy (Burnham, 1975) that provides kinetic energy for explosive volcanism and/or metamorphism. Evidence that base metal ore-forming solutions are derived from evaporated seawater circulating within fractures in continental crust (Wilkinson et al., 2005) strengthens the proposed model (Fig. 5). Rhyolite may form by melting of andesite layers (Tamura and Tatsumi, 2002) above granite bodies in a similar setting.

Decompression aided by water close to margin leads to normal arc magmas and formation of new continental crust. OIB magmas on the other hand are generated by decompression melting farther from the margin. Melt therefore bears characteristics typical of small amount of melting and also shows enrichment in fluid-insoluble Nb-Ta. The disparate character of arc magmas and continental crust vis-à-vis OIB with respect to Nb-Ta abundance (Weaver, 1991) can be explained by considering Nb-Ta enrichment as a pointer to magma generated under cover with no aid from water. This is the case with OIBs and continental rift-related basalts prior to breakup and entry of water. Composition of this magma approximates the unmodified composition of melt generated by decompression melting. Water is a great modifying agent leaving enormous mark on most other magma types, particularly evident in arc-related magmas. Arc magmas, even though evolve under cover, are modified by aqueous solution entering through crustal fractures. To summarise the trace-element geochemistry of basalts, OIB represent the original melt produced by a small degree of decompression melting, MORB represent a similar melt with some characteristics modified because of large degree of melting which results in overall dilution of incompatible trace-element concentration and arc basalts are products of melt modification by large degree of partial melting as well as seawater interaction. Plagioclase-phryic arc rocks with associated hydrothermal deposits result because of extensive decompression induced crystallisation accompanied by exsolution of volatile phases (Cashman, 2004) during final stages of magmatic activity at the folded margin. Repetitive episodes of rifting and suturing at the same weak zone (mobile belt) over a considerable geological time concentrate economic deposits. Precambrian mobile belts, representing a long time span and hence large number of iterations, are therefore storehouse of base-metal deposits.

At the folded margins, as matter is added to the continental crust, a water cycle is completed. It begins with mechanical fracturing of oceanic crust allowing the seawater in, which is followed by dissolution of water with magma under pressure, transport of magma toward continent and accumulation under the bulge, aiding magma modification and ascent, exsolution of volatiles with decompression, hydraulic fracturing of cover rocks and extrusion of rocks and volatiles. The cycle ends with deposition of hydrothermal deposits associated with arc rocks.

Occurrence of blueschist and other high-pressure rocks at the leading edge of so-called accretionary wedge can be explained as caused by compression of oceanic crust resulting from ridge-push. Distribution of high-pressure metamorphic rocks with respect to phases of extension and compression at terranes of western Alps (Rosenbaum and Lister, 2005) supports this hypothesis. In case of paired metamorphic belts, the belt closer to the continent is influenced by heat supplied by the cooling granitic magma, whereas in the other belt compressive forces play a major role. In both the belts,
Fig. 5. Flow diagram depicting the entire proposed paradigm as a continuous cycle of events. Solid arrows indicate the main sequence of events and events marked by dashed arrows are relatively less likely to occur. The three rectangles represent the three domains (continent, ocean and the active margin) where the events occur. Some major events have cross-domain impact such as continental breakup which results in creation of MOR and of new margins.
protoliths of metamorphic rocks are rocks similar to those of accretionary complex, including mafic and ultramafic rocks (Iwamori et al., 2007), which further indicates that the oceanic crust instead of being subducted is folded and accreted to the continent. The occurrence of low P/T metamorphism instead of regional high-grade metamorphism perhaps is indicative of cessation of ridge push during granite cooling. UHP metamorphic rocks of some regions have been found to be exhumed at exceptionally high rates (e.g., Parrish et al., 2006). The conundrum surrounding exhumation of UHP metamorphic rocks ceases to be a big issue if it is assumed that they are formed at higher levels by lateral compression than at deeper levels by vertical load because of burial. The paradigm of subduction tectonics makes exhumation difficult by assuming UHP rocks are formed at 80-100 km depths. The case for overpressure developing in compressive regimes and consequent mineral reactions forming eclogitic rocks has gained strength in the light of works by Mancktelow (1993) and Smith (1995). The dilemma of Austrheim and Boundy (1994) in explaining the brittle behaviour of eclogitic crust in Bergen Arcs, Norway is mainly caused by the presumption that eclogites formed at a depth of 60 km or more. Camacho et al. (2005) explain this with a cold-crust model where the continental crust is buried and exhumed in less than 13 million years thus ruling out possibility of thermal equilibrium. This is not necessary if the high-pressure metamorphic event took place at upper levels in the crust. Exhumation can be related to cessation of seaﬂoor spreading which results in relaxation of compression regime at the margin. This probably also explains the occurrence of metamorphic phase during tectonic mode switch from compression to extensive ductile regime as well as the global scale of operation of episodicity of these events (Lister et al., 2001) given that seafloor spreading usually operates on a global scale.

High-grade metamorphic rocks form along the sutures between the old continental crust and the newly emplaced granitic batholiths. Granite cooling supplies the heat which combined with compressive forces metamorphose the volcanic and sedimentary rocks deposited in earlier marginal basins. This explains why granulites are common around margins of ancient cratons. It is granite and not ophiolite that represents a suture zone. Ophiolites are mere remnants of oceanic crust. Highly deformed granulite zones are also the weak zones in continental crust ready to be reactivated by a future stress regime. The processes at the active continental margin can be summed up by the equation:

\[
\text{compression (push)} = \text{volume (between decoupled layers; room for granite)} + \text{heat (inside the volume; granite/granulite)} + \text{pressure (high-P metamorphism/granulite/deformation)}
\]

Overall, the system is an analog of a (reverse) heat engine with continental crustal block acting like a piston pushing and compressing the volume of the cylinder (space under the bulge at the folded margin). The result is melting of subcrustal material and production of a whole suite of magmatic and metamorphic rocks as well as economic mineral deposits with water acting as a change agent.

The striking coincidence between timing of ophiolite emplacement, high-P metamorphism and magmatism in Indo-Arabian region and that of disintegration of Gondwanaland (Gnos et al., 1997; Jan, 1991; Dunlap and Wysoczanski, 2001) provides a strong support to the paradigm. Also the sequence of events in the Himalaya – high-P metamorphism followed by thrusting of nappes and then regional metamorphism (Le Fort, 1996) – goes well with the paradigm.

Volume of melt generated by decompression at the uplifted continental region is limited by the space determined by the amount of uplift of continent before breakage and the lateral spread of decoupling between lithosphere and asthenosphere. Eventually the space/ﬂuid is reduced to null and spreading comes to a halt. Cessation of seaﬂoor spreading causes the folded margin to ‘relax’ upon withdrawal of the push. This can lead to dispersal of volcanic islands near the folded margin. A new tectonic cycle may begin when the passive margin cools sufficiently to develop a tendency to sink. Thus the proposed tectonic paradigm envisages a region of material eruption at the site of continental breakup which forms new oceanic crust and a region of material squeezing at the other end of the continent (folded margin) where old oceanic crust becomes part of the continental crust. I propose to name the paradigm as “bal tectonics” after a Sanskrit term “bal” (pronounced “bul”) which means “fold of skin” as well as “strength” and “force”.

Precambrian shield areas bounded by the mobile belts represent the bulges that hosted melts to produce granitic rocks sutured to the continents. The Abitibi belt provides an Archæan example of a greenstone belt hosting granitic plutons (Chown et al., 2002) similar to modern Japan. Archæan greenstones have been considered as older equivalents of modern arc rocks (Condie, 1997).

As it happens with many natural systems, there can be deviations from the above described idealized steps from start till finish of the cycle. The marginal downward pull may also cause uplift at the ocean side of the margin and, if the crust there is sufﬁciently rigid, fractures develop that lead to formation of ocean islands and in extreme cases spreading ridges. East Paciﬁc Rise (EPR) is likely to have resulted from ocean side crustal fracturing due to pull at the Andean margin. The resulting movement of oceanic crust toward the continent is exceptionally fast in this case as it was caused by a large pull necessary to overcome the strength of the oceanic crust and also partly because the pull does not have to spend energy dragging a continent along. Absence of central valley at the
EPR can also be explained by the fact that the site does not represent breakup of continent. Central valleys at other slow spreading ridges are vestiges of pre-breakup continental rift valleys left on the oceanic crust after the breakup.

If the margin is the result of a previously split continent, the marginal faults may be reactivated because of compression. Submergence under water of such reactivated faults may provide channels for water to enter sub-crustal regions thereby causing generation of basaltic fluids. With fluids forming very close to the continental margin, granite batholiths would form not far from the continent.

Hydrous partial melts contain higher SiO$_2$, lower normative olivine, lower FeO and lower MgO compared to anhydrous melts (Gaetani and Grove, 2003). Thus water has more role to play in the production of granitoids than coarse mafic rocks. If water-induced basaltic melt is not available to fill the void created by ridge-push, ultramafic melt from mantle is sucked in which forms ultramafic cumulate rocks as in many layered igneous complexes. Similarly in relatively dry near-surface conditions along uplifted continental regions, alkaline basalts, kimberlites and carbonatites may form because of decompression without much aid from meteoric water. Oceanic intraplate volcanism also can be similarly explained as caused by small-scale crustal upheavals in localized regions which are usually close to folded margins or MOR. The conundrum of long-lasting localised volcanism and lack of age progression expressed by Cenozoic volcanoes of New Zealand (Hoernle et al., 2006) does not exist if viewed in the light of the proposed paradigm.

**Crust or Lithosphere?**

One of the delicate issues during this synthesis has been to ascertain what gets folded: crust or lithosphere? In other words, where does the decoupling occur: between crust and mantle or lithosphere and asthenosphere? Seeking an answer to this probably requires an improved understanding of the interior of the Earth than is presently available. For simplicity, we can assume that lithosphere, which includes an increasing proportion of mantle with age and with distance from the MOR, is decoupled at the margin from the underlying plastic asthenosphere and hence is folded. It is however possible that

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**Fig. 6.** Digital elevation model of Andaman Sea and northern Sumatra using Shuttle Radar Topography Mission data showing cross-section along a line in northern Sumatra. The bathymetry/topography shows marked undulations which are traditionally termed as trench (T), outer arc (O), forearc (F), volcanic arc (V) and backarc (B). 90E = Ninetyeast Ridge.
the decoupling can occur, at least locally, between layers within the lithosphere or even within the crust. The current textbook vision of the lithosphere as a slab of uniform thickness needs rethinking.

**Criticism of the Paradigm**

An obvious criticism of the hypothesis is because of the firm establishment of the phenomenon of subduction among the scientific community. If there is no subduction, what are Wadati-Benioff zones then? Taking a few steps of interpretations and assumptions back, a Wadati-Benioff zone primarily represents a 3-dimensional region studded with earthquake hypocentres which most likely represent faulting by bending of rigid lithosphere/crust close to continental margin. The picture is not always as smooth as drawn on textbooks as there are many deviations from the standard Wadati-Benioff zone distribution of seismic activity. Shallow-focus earthquakes on the downdip side of Wadati-Benioff zone are often conveniently ignored. Another obvious question can be: what does seismic tomography reveal? Seismic tomography, as discussed above, clearly shows patterns governed by surface distribution of earthquakes hinting at different behaviour of earth materials under continents than under oceans in general at depths up to ~600 km. Cogency of tomograms further deeper is a matter of debate (Trampert, 1998). The cornerstone of the proposed paradigm is continental vs. oceanic lithosphere and their interfaces as opposed to rigid plates distributed across the globe. Finally, one may ask: where do we see the marginal folds described here? The folds conceived here are deemed to be represented by the putative subduction zones. The typical portrayal of subducting slab manifests one limb of the fold. The occurrence and appearance of the other limb depends on the stage of development of the margin. The overall fold system comprises of what are described in plate tectonics phraseology as forearc basin, accretionary prism, volcanic arc and backarc basin. For example, a panoramic view of these features can very well be perceived as folds in Sumatra (Fig. 6).

**Conclusions**

The proposed paradigm considers most tectonic activities to be centred around two types of linear features on the Earth’s surface. One of them is continental margin where the oceanic crust is folded which represents the same region as the putative subduction zone. The other feature -- the rift that usually begins as a continental uplift and continues after the breakup with ocean occupying the gap -- is retained from the plate tectonic theory. Further, the paradigm assumes that the two centres of tectonic activity are dynamically linked together. The old margin experiences a downward pull because of increase in density of oceanic crust. The pull tilts the continent on one hand and initiates a broad fold at the marginal oceanic crust on the other. Tilt results in uplift along a weak zone in the continent and extensional forces cause normal faults, basin subsidence and eventually breakup. Uplift leads to decoupling of subcrustal layers. Whereas adiabatic decompression is the main cause of melting of subcrustal material, near-surface water, entering deeper levels through crustal fractures, plays an important role in the generation, modification and emplacement of magma. Creation of zone of decompression, melting and emplacement can occur in various steps depending on specific conditions of a site. Breakup and spreading of the ridge pushes the continent away and the stress is passed on to the folded margin on the opposite side of the continent. The folded margin develops axial-plane faults along the crests and troughs as the folds get amplified because of the ridge push. Ridge push also causes high-P metamorphism. There is decoupling between subcrustal layers at the folded margin too which creates space between subcrustal layers. Melt generated by partial melting and seawater interaction with subcrustal material migrates towards this space and gets ponded. Melt ponding over a geological period forms granitic rocks due to differentiation and cooling. Accretion of granitic pluton to the continent is accompanied by high-grade metamorphism and granulite formation at the suture zones.

The topmost shell of the Earth is envisaged here as laterally divided into the conspicuous continents and oceans. Such a perception is favoured here in preference to division into plates as it reflects not only the strong compositional and rheological differences of the divided blocks (continents and oceans), but also most seismic tomographic results acquired so far. With this division, Earth matter can be treated, without any predisposition, similar to any other material and laws of physics and chemistry can be applied as normal. However, while applying such laws due understanding of the characteristics of matter at a point in the history of the region it belongs to (e.g., continental weak zones, young vs. old oceanic crust) is required.

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