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Active Tectonics of Western Continental Margin of Indo- Pak Craton – Stress Source for SCR Earthquakes

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Abstract

Western continental margin of Indo-Pak craton (WCMI) extends from the Mekran coast of Pakistan to Cape Comorin at the southern tip of India. The WCMI is bound by the Mekran Accretionary Prism in the north and the Comorin ridge in the south. The major structural elements from north to south are – E-W oriented Mekran thrust along Karachi coast, NE-SW oriented Murray Ridge, Deep Water Indus basin, Late Cretaceous Tansform Zone, and Saurashtra volcanic Platform, followed south by NW-SE trending Laxmi Ridge, Gop rift/Laxmi Basin, Indian continental shelf affected by Late Cretaceous rifting (following break up of African continental fragments, Seychelles-Madagascar), Chagos-Laccadive Ridge/Depression and Comorin Ridge/Depression. Rifted Indian shelf is styled by Shelfal Horst/Graben Complex and bordered by Kori-Pratap-Comorin Ridge and Kori-Comorin Depression. To the west extends the Arabian Sea, a spreading ocean across Carlsberg Ridge. The WCMI is a typical volcanic passive margin. This is evident from the occurrence of various intrusive and extrusive mafic igneous complexes which were emplaced during different stages of continental break up, particularly in the highly tectonised northern part of the WCMI. Anomalously high mantle temperature responsible for the volcanic margin appears to be related to crustal stretching, thinning and consequent mantle fracture coincident with the passage over the Reunion hotspot. The southern part of the WCMI is mainly associated with the hotspot trail (Chagos-Laccadive Ridge), related intrusives and underplating. Post collision blocking of northward drifting of the Indian plate, continued ridge push due to spreading of the Arabian Sea floor, and slab-pull from the Andaman-Sumatran trench are responsible for the present anticlockwise rotation of the plate, NNE-SSW oriented compressive intra-plate stress and reactivation of rift related faults. Continuing intra-plate stress is causing widespread tectonic inversion along reactivated faults in WCMI as well as in pericratonic rifts. NNW-SSE and ENE-WSW are the two dominant trends of the faults, the former is related to continental rifting and the latter is the older generation faults related to pericratonic rifting that developed during pre-break

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up crustal distension. Both fault systems are reactivated along primordial fractures in Proterozoic orogenic belts of the proto-craton. WCMI shelfal zone is much rifted by the longitudinal faults which are displaced by transverse faults reactivated at a later stage by rotational stress of the plate. Both the fault sets are undergoing transpressional movement in the current geodynamic set up.

The high intensity of faulting in the northern part, north of Narmada fault and rifting in the adjacent pericratonic region indicate more intensive tectonism in this part in the current cycle. Proximity of the plate convergence at Mekran thrust belt, transform motion along Owen fracture zone, Murray Ridge, Omach-Nai and Chaman fault zones, segmentation of southern part of Indus shelf by Nagar Parkar fault are responsible for the high degree of tectonics of this part. This is the source of stress generation in the adjacent pericratonic rifts in the north-western part of the Indo-Pak craton – Kutch, Cambay, Narmada and Saurashtra. These rifts with synrift deep seated plutons, undergoing structural inversion, are the main sources of stress build up for SCR earthquakes in India. In this paper, I discuss the intraplate fault kinematics related to the prevailing geodynamic set up. Contrary to the hypothesis of lithosphere bending in central Indian craton causing compression (Billham and Gaur, 2011), evidences show that the lithosphere is stretched and rifted and is undergoing inversion as in the case of other intra-plate rifts.

Keywords: Active Tectonics, SCR, WCMI, SONATA

1. Introduction

The Stable Continental Region (SCR) earthquake epicenters in peninsular India are located mostly in western India within Gujarat and Maharashtra states (Fig. 1). Much rifted region of Western Gujarat between Kutch and Narmada rifts is the home of high magnitude earthquakes. This region is also known for high seismic activity as indicated by continued aftershocks since 2001 Bhuj earthquake and continuing moderate to low intensity earthquakes in recent time. Kutch rift zone is the most strained zone as indicated by recent studies (Biswas and Khatri, 2002; Biswas, 2005). It seems logical considering its proximity to the most active part of the Western Continental Margin (WCMI) of Indo-Pak Sub-Continent.

The WCMI extends from the Mekran coast of Pakistan to Cape Comorin at the southern tip of India (Fig.2). The WCMI is bound by the Mekran Accretionary Prism in the north and the Comorin ridge in the south. This is a typical volcanic passive margin (White et al., 1987) that evolved as African and Indian plates separated during the break up of Gondwanaland (Norton and Schlater, 1979). Separation was in two stages; i) in the initial stage the African plate and Indian plate with the attached Madagascar-Seychelles fragments were separated in Early Jurassic. ii) In the final stage of break up during Late Cretaceous (88-65 Ma),

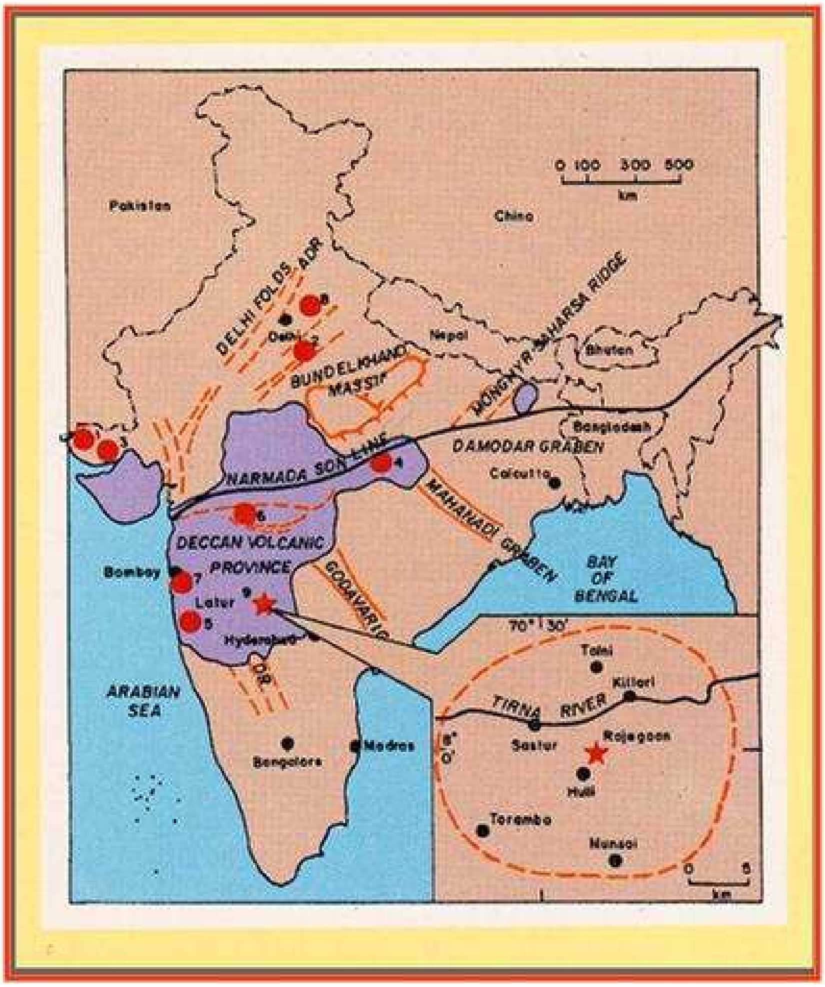

Figure1. **Generalised tectonic map of the SCR of India showing distribution of major earthquake epicenters in Western India, Deccan Trap covered region spreading over Gujarat and Maharashtra state bordering WCMI. Red circles indicate epicenters of eight high magnitude earthquakes. (After Gupta, 1994**).

Madagascar and Seychelles cratonic fragments separated from Indian craton giving final shape to the WCMI. Most of the volcanic events took place during the last stage of break up close to K/T boundary. This was the time of rift-drift transition marked by tectonic climax when several tectono-volcanic coeval events took place. Aborting of the pericratonic rift basin and consequent initiation of tectonic inversion took place by stages of upthrusting, transtensional and finally post collision transpressional episodes (Biswas, 2005). As the Indian plate continues to under thrust below the Asian plate with an anticlockwise rotation due to ridge push from the west and slab-pull towards the Andaman trench, the tranpressional stress continues till the present time (Fig.2), which is responsible for earthquake generation in the Indo-Pak sub-continent. In this article, the geodynamics and related fault kinematics responsible for strain build up in the western pericratonic region is discussed.

2. Tectonic Features of WCMI

The major structural elements from north to south are: E-W oriented Mekran thrust along Karachi coast, NE-SW oriented Murray Ridge, Deep Water Indus basin, Late Cretaceous Tansform Zone, and Saurashtra volcanic Platform (Biswas, 2008; Corfield et al., 2010) (Fig.3), followed to the south by NW-SE trending Laxmi Ridge, Laxmi Basin (Gop rift), Indian continental shelf (affected by Late Cretaceous rifting during break up of continental fragments, Seychelles-Madagascar), Chagos-Laccadive Ridge/Depression and Kori-Comorin Ridge/Depression (Fig. 4).

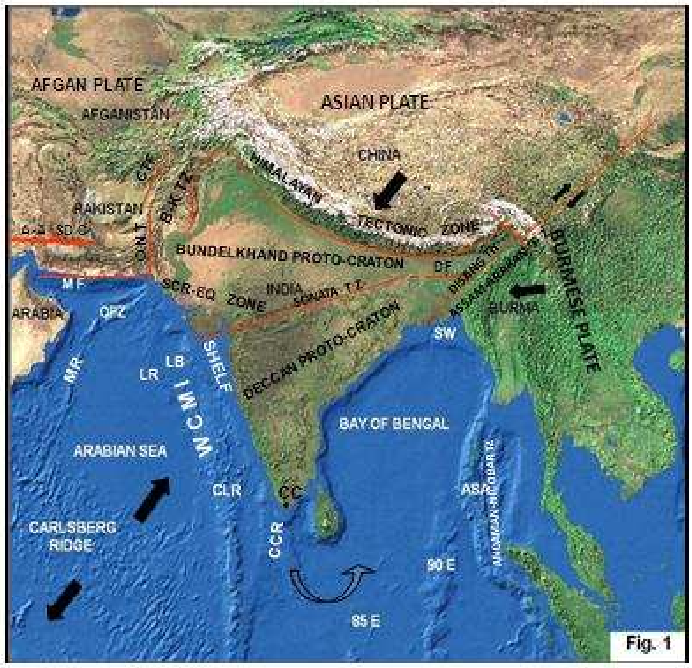

Figure 2. Tectonic map of India. WCMI: Western Continental Margin of India, BKTZ: Baluchistan-Karakoram tectonic zone, MF: Mekran fault, A-A SDC: Afgan-Arabian Ocean subduction complex, CTF: Chaman transfer fault, ONT: Ornach Nai transfer fault, OFZ: Owen fracture zone, MR: Murray ridge, LR: Laxmi Ridge, LB: Laxmi Basin, CLR: Chagos-Laccadive Ridge, CC: Cape Comorin, CR: Comorin Ridge, 80E: 80^{0}East Ridge, 90E: 90^{0}East Ridge, ASA: Andaman-Sumatran arc, SW: Swatch-of-no grounds (canyon), SCR EQ Z: Stable contiental region earthquake zone, SONATA TZ: Son-Narmada-Tapti Tectonic zone, DF: Dauki Fault. Black arrows indicate prevailing stress direction: Curved arrow indicate plate movement, See text.

Rifted Indian shelf is styled by Shelfal Horst/Graben Complex which is bordered by Kori-Comorin Depression and Kori-Comorin Ridge along the shelf edge (Fig.4). To the west, extends the Arabian Sea, a spreading ocean across Carlsberg Ridge. The WCMI is a typical volcanic passive margin (Corfield et al., 2010). This is evident from the occurrence of various intrusive and extrusive mafic igneous complexes which were emplaced during different stages of continental break up, particularly in the highly tectonised northern part of the WCMI. Anomalously high mantle temperature responsible for the volcanic margin appears to be related to crustal stretching, thinning and consequent mantle fracture and deep lithosphere melting coincident with the passage over the Reunion hotspot. The southern part of the WCMI is mainly associated with the hotspot trail (Chagos-Laccadive Ridge), related intrusives and underplating.

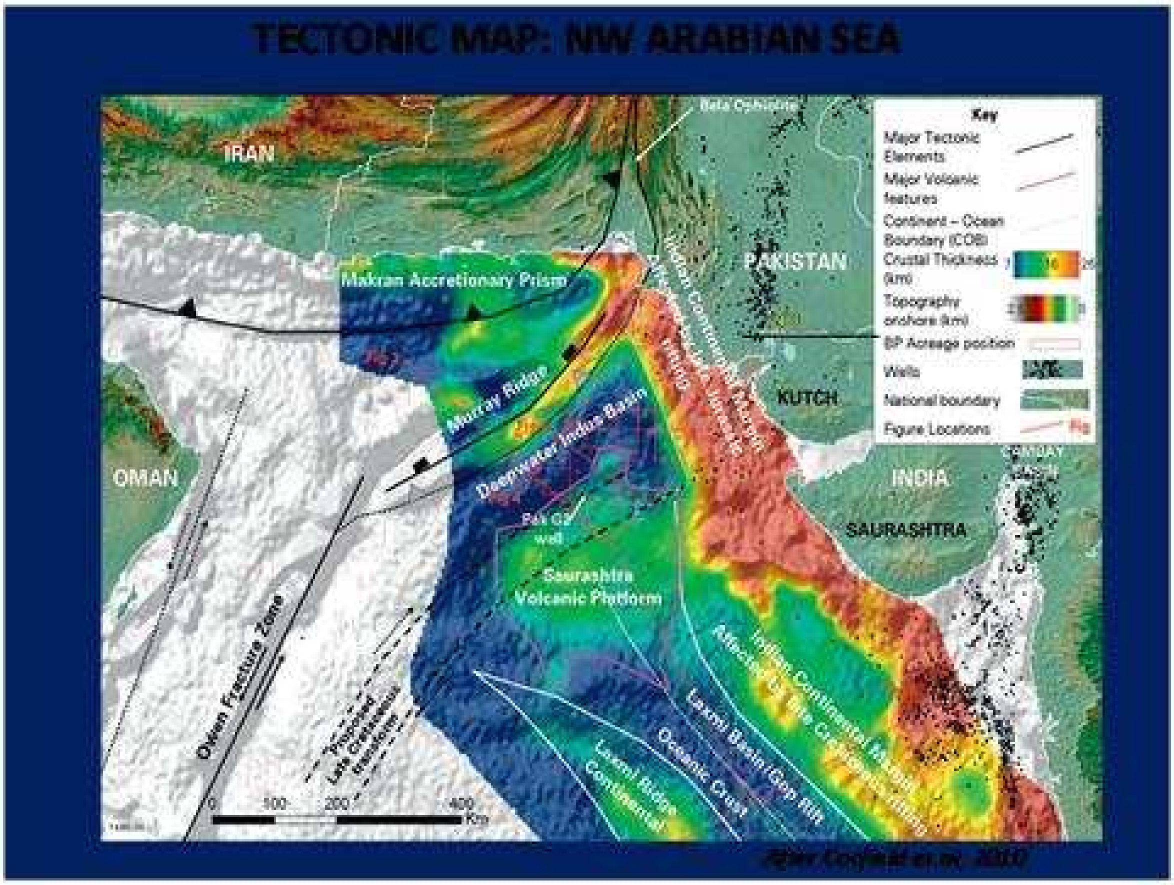

Figure 3. **Tectonic map of Northern WCMI. (After Corfield et al., 2010).**

3. Plate Dynamics

Post collision blocking of northward drift of the Indian plate, continued ridge push due to spreading of the Arabian Sea floor, and slab-pull from the Andaman-Sumatran trench are responsible for the present anticlockwise rotation of the plate, NNE-SSW oriented compressive intra-plate stress and reactivation of rift related faults. Continuing intra-plate stress is causing widespread tectonic inversion along reactivated faults in WCMI as well as in pericratonic rifts. Two sets of faults along NNW-SSE and ENE-WSW trends are dominant in WCMI. The former is related to inter-plate continental rifting and the latter is related to intra-plate peri-cratonic rifting. This ENE-WSW set of faults developed earlier during pre-break up crustal distension. Both fault systems are reactivated along primordial fractures in Proterozoic orogenic belts of the proto-craton, viz., Dharwar and Aravalli Proterozoic mobile belts (Biswas, 1987, Ramkrishnan, 2003). The WCMI shelf zone is much rifted by the longitudinal faults which are displaced by transverse faults reactivated at a later stage by rotational stress of the plate. Both the fault sets are undergoing transpressional movement in the current geodynamic set up.

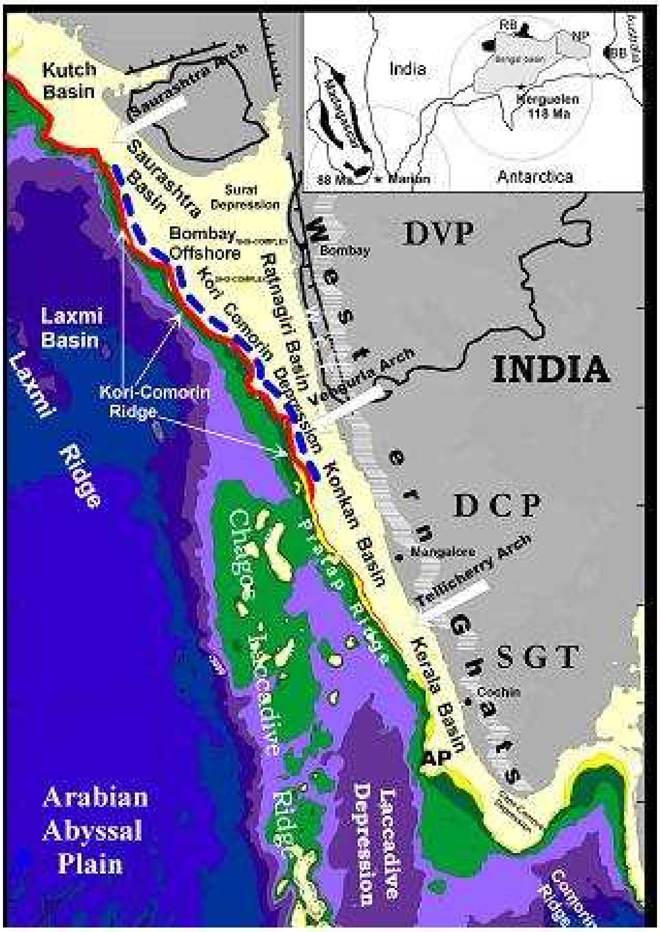

Figure 4: **Tectonic map of Southern WCMI. WCF: West Coast fault, DVP: Daeccan Volcanic Province, DCP: Dharwar Cratonic Province, SGT: Southern Ganulite Terrain.**

4. SCR Fault Kinematics, Plutonic Activity and zone of strain concentration

The high intensity of faulting in the northern part, north of Narmada fault and rifting in the adjacent pericratonic region indicate more intensive tectonism in this part. Proximity of the plate convergence at Mekran thrust belt, transform motion along Owen fracture zone, Murray Ridge, Ornach-Nai and Chaman fault zones, segmentation of southern part of Indus shelf by Nagar Parkar fault are responsible for the high degree of tectonism of this part of the subcontinent (Fig. 6). This is the source of stress generation in the adjacent pericratonic rifts in the north-western part of the Indo-Pak craton – Kutch, Cambay, Narmada and Saurashtra. These rifts with synrift deep seated plutons, undergoing structural inversion, are the main sources, of stress build up for SCR earthquakes in India.

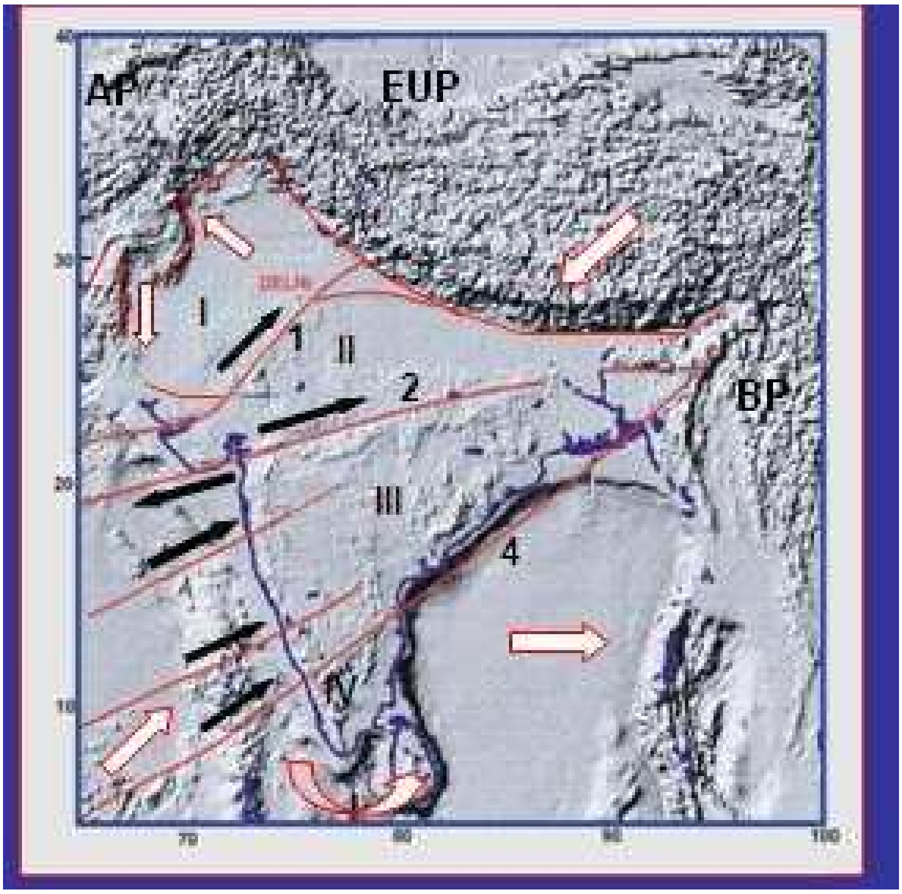

Figure 5: Geodynamic map of Western India showing kinematics of ocean-to-continent tranform faults along trans-continental mega-shear zones, 1: Great Boundary fault, 2: Fault along Sonata TZ, 3: Fault along Palghat-Bhawani-Eastern Ghat-Naga mega shear. I: Trans-Aravalli craton, II: Cis-Aravalli craton, III: Dharwar-Bastar craton, IV: Southern ganulite terrain. AP: Afgan Plate; EUP: Eurasian Plate; BP: Burmese Plate.

The activation and kinematics of the faults are related to the geodynamic set up as described above (Fig.2). The anticlockwise rotation activated three trans-continental faults along mega-shear belts across the Indian craton, from north to south are the Great Boundary fault, SONATA tectonic zone (Jain et al., 1995; Acharya and Roy, 2000) and Palghat - Bhawani-Eastern Ghat-Naga thrust tectonic lineament (Fig. 5). These faults extend offshore across WCMI. Apparently these faults are correlatable with transform faults of the Carlsberg Ridge (Biswas, 1993, 2003 and 2008) and thus could be defined as trans-continental transform faults. These three faults divided the craton into four blocks. The SONATA belt is the paleosuture between Bundelkhand Proto-craton (BPC) in the north and Deccan Proto-craton (DPC) in the South (Fig. 2). The movement of BPC is constrained by the collision front while the DPC is moving more freely after reactivation of the suture (Fig. 7).

Figure 6. Geodynamic map of Northwestern Indo-Pak craton showing important stress direction. CT: Chaman Tansform fault; ONT: Ornach Nai Transform fault; AP-AOP: Afgan plate-Arabian ocean plate; BR: Badin rift ; TFR: Thar fossil rift; NPF: Nagar Parkar Fault.

This relative rotational movement created differential stress regimes as shown in the figure. In the east, a more compressive stress zone is causing inversion of the eastern Gondwana basins while in the west extensional stress system is responsible for opening up pull-apart basins, Olpad-Kosamba grabens in offshore Narmada regime (Rangarajan, 2004). Due to blocking of the BPC and free movement of DPC the strike-slip movement along the reactivated Narmada shear is dextral while that along Cauvery-Naga thrust is left lateral (Fig. 5). This relative slip of the blocks between faults is responsible for the westward convex outline of the present west coast of India as shown in Fig.5.

5. Zone of SCR Earthquake in Indian Sub-continent

The northern part of the WCMI is highly tectonised due to its proximity to the active collision zone of Afghan and Indian plates along a transform margin defined by Chaman and Ornach Nai faults.

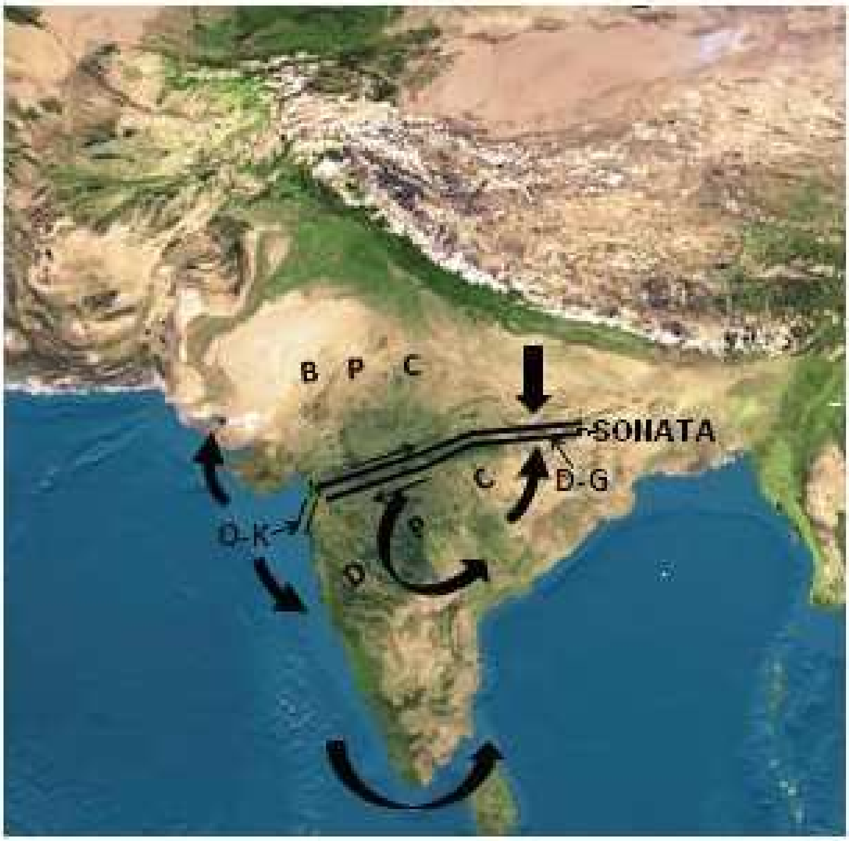

Figure 7. Indian continental plate showing relative intra-plate rotation across SONATA zone. N: Narmada rift, O-K: Olpad-Kosamba graben complex, DG: Damodar graben. Ararows indicate stress directions.

Apparently, these faults were developed during the post collision rotational motion of the Indian plate. Active Mekran thrust is the northern boundary of WCMI. Ornach Nai and Owen transform faults separate the under thrusting and transform plate boundaries. The Nagar Parkar strike slip fault (NPF) appears to be a transform fault continuous with the Mekran thrust across the Owen fracture zone after displacement (Fig.6). Transform motion along NPF has been induced by the rotation of the Indian plate. In this set up the NPF is an important tectonic zone marking the boundary between the foreland-orogenic belt in the north and rift zone in the south. This rift zone falling within the Gujarat state is in the inversion mode with the rift faults inverting into transpressional strike slip faults. Evidently, this is the main SCR earthquake zone in Indo-Pak sub-continent. Tectonic movement is simpler in the South of Narmada fault. In this part of WCMI, the rotational plate motion is activating the existing faults and NNE-WSW compressive stress is causing inversion.

The compressional stress causing structural inversion and neotectonic uplifts are due to plate dynamics and not due to any lithospheric bending as postulated by Billham and Gaur (2011). Deep Seismic Sounding profiles (Fig.8) across Central Indian plate (SONATA Zone) show uniform depth of Moho approximately at 40 km depth with flat lithosphere across SONATA Zone (Kaila et al., 1985). Evidences of structural inversion are also noticed along major faults of the Narmada rift (Fig. 8).

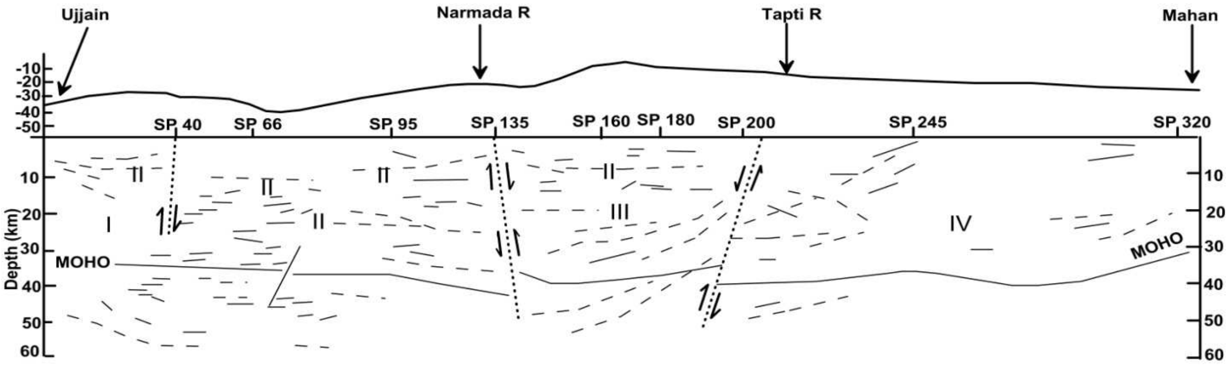

Figure 8. Deep Seismic Sounding profile across SONATA tectonic zone, showing flat Moho along crust-mantle boundary and reverse movements along normal rift faults due to inversion.

There is no indication of mantle bending, arching and crustal thinning in Jabalpur-Latur-Bhuj area as depicted by them. The underthrusting Indian plate was tilted and dragged towards the Himalayan trench due to slab-pull. No crustal bending was involved in underthrusting of the Indian plate below the Asian plate. The crustal bending along the outer margin (platform-basin boundary) of the northern foreland basin creating Ganga-Bramhaputra arches, took place due to subsequent tectonic loading on the subduction complex as it is common in all cases of foreland basins. High gravity values across central India are due to the crustal underplating related to Reunion hot spot event.

6. Conclusion

The WCMI is an active volcanic passive margin. Continued tectonic movement is due to present plate motions. The northern part of the continental margin, north of Saurashtra, is located in a critical zone where Arabian Sea plate is thrusting under the Afghan plate along Mekran Thrust and to the east of this under thrusting plate, Indo-Pak craton is slipping along the Chaman-Omach Nai transform fault (COTZ) against the Afghan plate due to anticlockwise rotation of the Indian plate. The COTZ appears to be the northward continuation of Owen Fracture Zone as an important ocean to continent transform zone defining a transform plate boundary. Presumably, the Nagar Parkar fault (NPF) is the eastern extension of the Mekran fault after being displaced by the Owen transform fault. This fault is also an important transform boundary between the subducting plate on the north and much rifted pericraton on the south, i.e., Indus foreland-Karakoram orogenic belt and Kutch-Cambay-Narmada-Western offshore rift zone. The plate rotation is generating dextral transpressional strike motion along NPF. The plate is much strained under the compressive stress due to resistance from the collision front and ridge push from the Carlsberg Ridge and slab-pull towards the Andaman-Sumatran trench. The Narmada fault is another important tectonic boundary as an ocean to continent transform fault between the much stressed northern part of the WCMI and uniformly stressed southern part undergoing only rotational motion aided by the slippage along intra-plate trans-continental faults.

The complex geodynamics in the north WCMI due to complicated movements along several thrust and transform faults is responsible for much stress creation in the adjacent pericratonic rift zone which is much strained and consequently the most earthquake prone area for SCR earthquakes in Indo-Pak subcontinent. Widespread synrift plutonic activity created several surface and subsurface plutonic bodies. The deep seated plutonic bodies close to major faults are stress barriers and potential locales of earthquake generation as in the case of 2001 Bhuj earthquake (Biswas, 2005; Mandal and Chadha, 2008). The syntectonic plutonic activity climaxed in Late Cretaceous during final stage of Indian plate break up coincident with the passage over the Reunion hot-spot.

Contrary to the hypothesis of lithosphere bending in central Indian craton causing compression (Billham and Gaur, 2011), evidences show that the lithosphere is stretched and rifted followed by inversion as in the case of other intra-plate rifts (Hansen and Nielsen, 2003). In fact the entire Indian plate is under compressive stress due to plate motion.

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