Indo-Eurasian Plate collision and the evolution of Pak-Iran Makran Microplate, Pishin-Katawaz Fault Block and the Porali Trough*

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Abstract

Interpretation of tectonics of Indian and the Eurasian Plate reveal presence of a microplate west of the northward drifting Indian Plate (IP) by Early Eocene, which was subsequently accreted to the Eurasian Plate (EP) to occupy its southwestern margin. This microplate is designated as Pak–Iran Makran Microplate (P–IMM). By Early Eocene, the P–IMM, the Central Iran/Lut and the Afghan microplates kept pace independently with the northward drifting Indian Plate and later coalesced with the EP. The P–IMM that represents the southwestern block of the EP is situated between the Zendan Fault in Iran and the Ornach–Nal Fault in Pakistan. The eastern part of P–IMM is represented by the Makran Flysch Province (MFP) in Pakistan. The northern border of P–IMM coincides with the Jiroft Fault in Iran, which is interpreted to extend eastward along the northern margin of the MAP and most likely joins/truncates along the Chaman Fault.

By Oligocene, the converging IP and the Afghan microplate bordered a NE–SW oriented sea, with P–IMM in the SW. This ‘Remnant Closing Sea’ (Neo-Tethys) received Oligocene–Miocene flysch mainly from the NE, and is now represented by the Pishin-Katawaz Fault Block (P–KFB). This entire set-up was exposed to a synchronized dynamic environment. The plates were converging, the Oligocene–Miocene depositional trough was shrinking, the IP’s western collisional zone was evolving, Porali Trough was opening as the IP was rotating anti-clockwise, followed by the post- Miocene E–W compression in a transgressional setting. In this setting, the initially NE–SW oriented Pishin–Katawaz trough was elongated and compressed, sandwiched between the IP and the Afghan microplate. The left–lateral Chaman Fault (CF) and its northern extension, the Moqur Fault in Afghanistan mark the boundary between Afghan microplate and the Pishin–Katawaz Fault Block. In the southwest, the Pishin–Katawaz deposits are in geological continuity with the P–IMM through an elongated narrow zone. The eastern margin of P–KFB is faulted, along the Quetta Fault System (QFS), against the collisional margin of the IP (Figure 1). The collisional margin is traditionally described as the Axial Belt. It constitutes of a mix of sedimentary rocks where ophiolite obducted across the K–T Boundary and it is also interbedded with volcanics and colored mélanges, which are imbricated because of Himalayan orogeny. It is proposed to designate the collisional zone as Western Belt (Ex-Axial Belt), which is proposed to represent the western geological province of the Indus Basin. This entire kinematic and dynamic history is spread over a period of approximately 55 Ma.

Introduction

The initiation of collision of the Indian Plate (IP) with the Eurasian Plate is a late Cretaceous (Maastrichtian) event. However, the continent-to-continent collision, which raised the Himalayan Ranges, is considered to be initiated in the Middle Eocene (Molnar and Tapponnier (1975); Powell, 1979). Prior to the main collision with Asia, the Kohistan-Ladakh Island Arc (K–LIA) evolved on the northern extremity of the IP, wherein its calc-alkaline volcanic arc igneous activity ended by 61 Ma (Khan, et. al., 2009). This combined north-moving tectonic plate was of conical shape that was the first to collide with the Eurasian Plate in an oblique manner that initiated the onset of Himalayan collision zone. Along this northern margin, the crystalline oceanic/transitional crust of IP was first subducted under the Eurasian Plate followed by the deformation of K–LIA due to the continued northward drift of the IP. The collision zone in North Pakistan is represented by the K–LIA sandwiched between the EP and the IP. The contact between EP and K–LIA is marked by the Main Karakoram Thrust (MKT); whereas the contact between K–LIA and the IP is represented by the Main Mantle Thrust (MMT). Although IP is not in direct contact, on surface, with the EP in Pakistan, but its leading edge may be in contact and in a state of collision with the EP along a subduction zone (Khost–Waziristan, Kohistan, Chaman, Kunar, Katawaz, Yasin ophiolites) resulting in duplication of crust in the Himalayas and the Karakoram.

The western margin of the IP is considered to be in an early stage of oblique collision with the EP. The oblique collision and/or transpression resulted in the development of Chaman/Ornach-Nal Fault and the Quetta Fault System with the presence of sporadic outcrops of ophiolite mainly along the latter and a zone of sedimentation in between the two, which is dominated by the presence of marine clastics termed as Khojak flysch. This zone of sedimentation and deformation, recognized as the Pishin–Katawaz Fault Block (P–KFB), is sandwiched between the EP (Afghan microplate) and the IP. The contact between EP and P–KFB is marked by the Chaman–Moqur Fault; whereas the contact between P–KFB and the IP is marked by the QFS (Figure 1). Thus, the EP (Afghan microplate) and the IP are not in direct contact due to the presence of P–KFB in between. However, leading edge of the passive margin of the IP is considered to extend as far to the northwest as the Afghan microplate below the overthrusted P–KFB with the presence of about 57 km thick duplicated crust of the Afghan microplate (Jadoon and Khurshid, 1996). The deposition of Khojak flysch in P–KFB is a result of deposition of Oligocene–Miocene shallow marine sediments in deltaic environments supplied by the Proto-Indus River, in a shrinking basin along the western margin. The depositional basin is considered to extend southward across Porali Trough, which is interpreted to be elongated in an E–W orientation due to the anti-clockwise rotation of the IP.

The closing basin (‘Remnant Sea’ of the Neo–Tethys) covered the margins of both IP and the Afghan Block (part of EP). It has resulted in the deposition of regressive cycles of Cenozoic sedimentation of P–KFB, on top of the Mesozoic stratigraphy of the Indus Basin along the western collisional margin of the IP with obducted ophiolite in between.

PAK-Iran Makran Microplate (P-IMN)

Evolution

An animation of drifting plates by Shell International (not in public domain) shows presence of a new microplate, besides Iran/Lut/Afghan blocks, close to the western margin of the IP during Early Cenozoic. This microplate is now located south of Iranian/Lut/Afghan microplates, to which it had finally accreted. A combination of six time-lapsed snap-shots from this animation show how tectonic microplates including

Afghan Block and Iranian/Lut microplates have been present, drifted, and accreted to the EP during Cenozoic time (Figure 2). The new microplate, as inferred by the Shell Animation, is hereby named as Pak–Iran Makran Microplate (P–IMM). Its accretion with the Iran and Lut blocks is supported by the presence of a conspicuous east–west zone of ophiolite along their southern margin, marked by the Jiroft Fault (Aubourg, et. al., 2004). This boundary is extended further to the east as a plate boundary between Chagai calc-alkaline volcanic belt and the Makran flysch basin (Powell, 1979) (Figure 3).

Extent of Pak–Iran Makran Microplate

The P–IMM is a fault-bounded block of inferred oceanic lithosphere, possibly a fragmented part of the Neo–Tethys with surface exposures of Eocene to Pliocene and younger sedimentary rocks. These marine flysch deposits were folded and faulted in the early Pleistocene (Kazmi and Rana, 1982). Deposition and deformation of these deposits is attributed to the development of Makran Accretionary wedge/prism (Burg, et. al., 2011) along a subduction zone, which marks the southern boundary of the P–IMM in the offshore (Oman Trench). Its E–W limits stretch from NS oriented Zendan Fault in Iran (Aubourg, et. al., 2004) to the Ornach–Nal Fault in Pakistan. Whereas, its northern limit is represented by the E–W oriented Jiroft Fault in Iran, which is marked by the presence of ophiolite along the southern margin of Central Iran/Lut microplates in Iran (Figure 3), and inferred as a plate boundary between Chagai calc-alkaline volcanic belt (including the Kharan Fore-arc Province) and the Makran Flysch Province (Powell, 1979; Kazmi and Rana, 1982). Why ophiolite is present along the southern margin of the Central Iran/ Lut microplates and the Jiroft Fault in Iran and absent eastwards in Pakistan may be related to the absence of their sub-aerial exposure in Pakistan. However, the ophiolite has been reported from Raskoh, Bunap area (Hunting Survey Corporation, 1960; R. H. Siddiqui, 2004, unpublished PhD dissertation), and in its south (M. Iqbal Khan, 2012 written communication). Figure 3 is a montage of interpreted surface and subsurface evidence of the above statements.

Kinematic Model of P–IMM

A kinematic model, inferring the tectonic development along the Makran convergence and the P–IMM, is proposed in Figure 4. The model depicts presence of Neo-Tethys Ocean separating the Afghan Block (AB) and the Arabian Plate (AP) during the Late Jurassic (Figure 4A). In the Cretaceous, establishment of a subduction zone at the western edge of the Indian Plate is interpreted, mainly due to the presence of Kandahar calc–alkaline arc volcanism in the Afghan Block (Figure 4B). The root zone of this igneous activity is now exposed as an approximately 300 km long granodioritic pluton extending from Kandahar to Kabul with NE–SW orientation (Hunting Survey Corporation, 1960; Jacob and Quittmeyer, 1979). The Late Paleocene–Present (Figure 4C), spanning 55 Ma is represented by multiple tectonic episodes with the establishment of the Makran convergence zone, possibly due to the subduction of newly established P–IMM as the drift of the Indian subcontinent continued. This is inferred by the presence of Late Paleocene to Early Eocene andesitic volcanism of the Chagai arc and associated igneous activity with the occurrence of Cretaceous–Oligocene marine sedimentary rocks interbedded with lavas, tuffs, and agglomerates intruded by mafic and felsic igneous rocks. Granodioritic intrusions representing the core zones of volcanism are exposed in the Chagai arc (Meisssner and Rehman, 1973; Hunting Survey Corporation, 1960; Kazmi and Rana, 1982; Jacob and Quittmeyer, 1979). This period may represent the shift of Cretaceous Kandahar arc subduction system to the Cenozoic Chagai arc volcanism, with the establishment of the P–IMM and the development of Jiroft Fault (suture) with the emplacement of the ophiolite along the southern end of the Iranian/Lut blocks, which are not yet sub-aerially exposed in Pakistan (Figure 3).

In the Pakistan part of the Makran convergence zone, the plate boundary of the newly inferred P–IMM is marked between the Kharan Fore-arc Province (KFP) and the Makran flysch zone (Powell, 1979). Although the ophiolites are not exposed at the surface, however, they are inferred to be associated with the oceanic lithosphere overlain by the flysch deposits. The flysch deposit supply of terrigenous sediments was from the Lut, Afghan, and the Indian subcontinent (Jacob and Quittmeyer, 1979). These sediments, which are interpreted to be deposited in a marine setting over subducting oceanic lithosphere, since Oligocene, are deformed and duplicated in the Makran Accretionary wedge/prism. The accreted microplates (Afghan, Lut, and Iran) are now subjected to Quaternary volcanism with the establishment of present day Makran subduction zone along which the oceanic crust related to the Arabian Plate is being subducted along a gentle benioff zone underneath the P–IMM, which is now part of EP (Figure 5). As a result, the present volcanic arcs, with active centers of Bazman and Taftan in Iran and Sultan in Pakistan are apparently built upon the older volcanic arcs with a wide trench arc gap due to a gentle subduction zone. Thus, our model considers southward shift of the subducting zone along the Makran subduction system. The present day Makran subduction zone is considered to mark the southern boundary of the oceanic P–IMM with the Arabian Plate.

Pishin-Katawaz Fault Block (P-KFB)

Previous Work

The region is variously described in the literature as Kakarkhorasan flysch basin (Kazmi and Rana, 1982); Khojak flysch belt (Farah et. al., 1984); Pishin rear depression (Raza et. al., 1989); Pishin Median basin (Ahmed, 1991) and Makran–Khojak–Pishin flysch trough (Bannert and Raza, 1992) etc. However, the name adopted by (Bannert and Raza, 1992) indicates that they also do not consider Pishin area to be a separate entity and consider P–KFB to be in geological continuity with the Makran Flysch Province (MFP), or the P–IMM as designated in the present study.

Evolution

By the Oligocene, the converging IP and the Afghan microplate are interpreted to be separated by a NE–SW oriented sea, with the presence of P–IMM in the SW. This ‘Remnant Closing Sea’ (Neo–Tethys) received Late Eocene–Miocene flysch mainly from a northeasterly source brought by the Proto-Indus River, which is now represented by the Pishin–Katawaz Fault Block (P–KFB). This entire set-up was exposed to a synchronized dynamic environment that lasted from Eocene–Miocene and still continuing in a subtle manner. The plates were converging, the Oligocene–Miocene depositional trough was shrinking, the collisional margin of the IP was evolving, Porali Trough was opening as the IP was rotating anti–clockwise, followed by the post-Miocene E–W compression in a transgressional setting. In this setting, the initially NE–SW oriented Pishin–Katawaz trough was elongated and compressed, sandwiched between the IP and the EP (Afghan microplate). The northward drift of the IP caused the deformation of P–KFB resulting in the NNE-SSW structural trend as we see it today. The southwestern part of this fault block was elongated along a narrowed continuation of the Khojak flysch-zone. The southwestern tip of the P–KFB is around 28°15’:65°45’ in Pakistan, where it is most probably in geological continuity with the P–IMM across minor faults (Figure 1 and Figure 6).

P–KFB is interpreted to represent segmented oceanic/transitional crust related to the NW margin of the Indian Shield, on top of which the sedimentary rocks were deposited, with possible presence of ophiolite in between. However, the contact is inferred to be tectonized due to the subduction.

General Description

From NE to its SW tip, the total length of the mega fault block (P–KFB) is about 825 km, which is spread across Afghanistan and Pakistan. Its maximum width is about 200 km that falls mostly in Pakistan. The northern part in Afghanistan is designated as the Katawaz Fault Block (KFB) (Schreiber et. al., 1972), and its southern continuation in Pakistan is proposed to be called the Pishin Fault Block (PFB), in the present study as the block is sandwiched between the two fault systems (Figure 1). The combined name is proposed as Pishin–Katawaz Fault Block (P–KFB). P–KFB (including Porali Trough) is envisaged to represent a marginal zone of Indus Basin.

The P–KFB is bounded by faults from all sides (Figure 1). The fault block is bounded in the northwest by the Chaman–Moqur Fault and in the east and southeast by the Quetta Fault System (Ganss, O., 1966; Schreiber et. al., 1972). This mega fault block wedges out towards north, and in the southwest is linked with the P–IMM across minor faults, as seen on the surface.

Quetta Fault System and the Western Belt

The Quetta Fault System (QFS) of Schreiber et. al., (1972) equates to Ghazaband–Chiltan–Zhob–Chukhan Manda–Shinghar faults system (Kazmi and Rana, 1982) that marks the surface boundary between the P–KFB and the western collisional margin of the IP, which is proposed to be designated as the Western Belt instead of the ‘Axial Belt’.

Stratigraphy

The fault block is filled with 4–6km stratigraphically thick sequence of flysch, deltaic and molasse type of sediments (Shah, 2009), which is represented by the Khojak Formation (mainly Oligocene) that overlies the Nisai limestone (Eocene). Khojak Formation is divided into two members, namely Murgha Faqirzai member (shale/clay, lower Oligocene) and Shaigalu member (sandstone, Oligocene–Miocene). Shaigalu sandstone crops out throughout, except the limestone of Nisai Formation (Eocene), which is exposed at the eastern and the southeastern extremity of the fault block. An exploratory well (Ramadan-1) drilled to more than 4,000 m in the PFB remained within the Khojak Formation, without encountering the targeted Nisai limestone.

Dynamic Environment

It may be noted that the P–KFB, since its initiation in Eocene/Oligocene has remained in the same setting of the surrounding tectonic plates namely, Afghan microplate, Indian Plate and the P–IMM. This entire set-up, due to the dynamism of the converging plates may have shifted from its original geographical location, but basically remained one group of microplates that moved in unison with relative movement within. The P–KFB flysch was under stress since the deposition began in the originally NE-SW oriented trough. The syn- and post-depositional deformation has led to the folding and faulting as we see them today. It is envisaged that the original NE–SW trough was elongated due to convergence, which probably resulted in the NNE–SSW orientation of the present day P–KFB and the development of the Quetta Fault System along the junction of P–KFB and the collisional margin of the Indian Plate. Figure 6 is a simplified cartoon for the evolution of P–KFB, and the surrounding plates.

Kinematic Model of P-KFB

An evolutionary model of tectonic development along the western margin of the Indian Plate across the P–KFB, based on gravity modeling, is presented in Figure 7 (Jadoon and Khurshid, 1996). The model shows about 15 km thickness of structurally duplicated sediments above a decollement in an allochthonous Pishin–Katawaz flysch zone between Muslimbagh ophiolite and the Chaman–Moqur Fault, herein called as P–KFB (Figure 1). Shortening of about 353 km is measured by cross-section balancing between slope and shelf facies south of the Muslimbagh ophiolite. The shortening along the ophiolite and the Khojak flysch is in addition to this calculation. Thus, P–KFB is interpreted to be presently located several hundred kilometer south of its original depocenter and is therefore interpreted as an allochthonous block.

The model presented in Figure 7 shows evolution of an Atlantic type passive continental margin in Jurassic (Figure 7A). This is followed by convergence with subduction of Neo-Tethys oceanic lithosphere along the southern margin of paleo-Asia (Figure 7B), with mid-Cretaceous Kandahar andesitic arc volcanism (Debon et. al., 1986). Oblique collision of the northwestern margin is interpreted to be initiated by the Paleocene–Early Eocene emplacement of the Muslimbagh ophiolite. This event is constrained by the emplacement of ophiolite over Maastrichtian sediments and the onlap of Eocene platform strata (Figure 7C) (Allemann, 1979; Otsuki et. al., 1989).

The presence of Mid-Atlantic Ridge (MAR–type) basaltic lava flows mixed with distal deep-marine facies of Triassic rocks in the ophiolite shows that these rocks were scraped from down going plate and transported southeastwards due to convergence. These exotic facies now juxtapose shallow-water marine facies. The Khojak flysch was deposited on the remaining oceanic lithosphere during Eocene and the Late Oligocene, with the early Himalayan uplift as the most likely source (Qayyum et. al., 1996). Continued oblique convergence resulted in the closure of the ocean basin, the initiation of the left-lateral strike-slip Chaman Fault system, and deformation of the Khojak flysch (Figure 7D). Finally, ongoing convergence has resulted into the deformation of the passive-margin of the Indian Plate and onset of molasse sedimentation since Miocene (Figure 7E). The model presented in Figure 7E shows present configuration of the northwestern margin of the Indian Plate based on the structural interpretations and gravity modeling (Jadoon et. al., 1994; Jadoon and Khurshid, 1996). The model shows tectonic blocks as the Sulaiman fold belt developed over transitional crust of the Indian Plate and the proposed P–KFB between Chaman Fault and the Muslimbagh ophiolite. The P–KFB is interpreted as a wedge of oceanic lithosphere and dominant marine clastic sedimentation sandwiched between Indian and the Eurasian Plates. The oceanic lithosphere in the wedge is transported and deformed with sporadic aerial distribution of ophiolite in Waziristan, Muslimbagh, and Bela. About 500 km of minimum, generally southeastward displacement of rocks is inferred along the P–KFB, which requires further evaluation, by paleomagnetic studies.

Porali Trough

The Porali Trough is considered as a product of the anti–clockwise rotation of the Indian Plate during collision. The deposition of Eocene–Miocene marine deposits may have occurred in a tongue of sea that kept widening as the plates translated. The translation also carried the Bela ophiolite belt eastward, which is now exposed along the eastern margin of the trough (Figure 1). A 2D seismic section across the Porali Trough is shown in Figure 8. The seismic reflectors are interpreted to represent Khojak Formation and the Eocene rocks overlying the basement; however, the interpretation of basement is questionable, as it is not exposed on the eastern side of the trough. The seismic reflectors in central part of the section are featureless, which may be due to the widening of the trough with time but within the plastic limit of the sediments that may explain the absence of the normal faults (Figure 8).

The Porali Trough is also interpreted to represent segmented oceanic/transitional crust related to the NW margin of the Indian Shield, on top of which the sedimentary rocks were deposited, with possible presence of ophiolite in between along an inferred tectonized contact.

Bela Ophiolite Belt

As discussed, the belt translated to the east due to the anti-clockwise rotation of the IP. It now occupies the eastern margin of the Porali Trough (PT). The Western Belt, through PT, is interpreted to be restricted to the Bela ophiolite belt, and hence the QFS is inferred to follow the western limit of the Bela ophiolite belt (Figure 3).

P–KFB and Porali Trough – Analogues

The only difference between the two is that the P–KFB evolved in a converging environment while the Porali Trough is a product of the anti-clockwise rotation of the IP. However, both are interpreted to represent segmented oceanic/transitional crust of the NW margin of the Indian Shield, on top of which similar type of sedimentary rocks were deposited, with possible presence of ophiolite in between. In this setting, both may be considered as analogues. The sediments of P-KFB and Porali Trough were deposited along/on the zone of subduction between EP and IP, with the sediment supply mainly from Proto-Indus River. P–KFB and Porali Trough are envisaged to be connected by a narrowed zone of subduction.

Conclusions

1. The P–IMM is inferred to represent a microplate west of the Indian Plate that had accreted with the Eurasian Plate (Iran/Lut/Afghan microplates) by Eocene time.
2. Jiroft Fault in Iran and its eastward continuation along the northern part of the Makran Accretionary Prism marks the northern boundary of the P–IMM.
3. Ophiolites are mapped along the Jiroft Fault (southern margin of the Central Iran/Lut microplates). Whereas, they are reported from Raskoh Range, as evidence of the plate margin and may be present in subsurface along the eastern continuation of the Jiroft Fault.

4. Zendan Fault in Iran and the Ornach–Nal Fault in Pakistan mark the western and the eastern boundary of the P–IMM, respectively. The southern boundary coincides with the subduction margin with the Arabian Plate (Oman Trench).
5. Pishin–Katawaz Fault Block is interpreted to represent segmented oceanic/transitional crust related to the NW margin of the Indian Plate. Presently, it extends across Pakistan and Afghanistan in a NNE–SSW orientation, with dominant deposition of marine Oligocene–Miocene clastic sedimentation (flysch) supplied by the Proto-Indus river, which is interpreted to be in geological continuity with the flysch in P–IMM.
6. The Chaman Fault and the Quetta Fault System are interpreted to represent the NW and the SW limits of the P–KFB. P–KFB is thus, a fault bounded block sandwiched between the EP and the western collisional margin of the IP. It represents marginal zone of Indus Basin.
7. Tectonic modeling across P–KFB shows its evolution with shift of subduction zone, from southern edge of Afghan microplate with the development of dominant strike-slip Chaman Fault in the west to the Quetta Fault System along the eastern boundary, with the emplacement of ophiolite along the NW margin of the IP.
8. P–IMM is tectonically interpreted with the inference of a shift of subduction zone along the Makran convergence zone, similar to the P–KFB.
9. Seismic interpretation and gravity modeling with inference of the top and bottom of basement across the Makran convergence zone is recommended for crustal variation and modeling across the Makran convergence zone.
10. The P–KFB and the Porali Trough are analogues, which are inferred to represent marginal zones of the Indus Basin. The sediments overlie the zone of subduction between EU and IP.
11. The Western Belt (Ex-Axial Belt), through the Porali Trough, is probably restricted to the Bela ophiolite belt. The QFS, thus, follows the western margin of the Bela ophiolite belt.
12. The Western Belt is considered to represent the western geological province of the Indus Basin.

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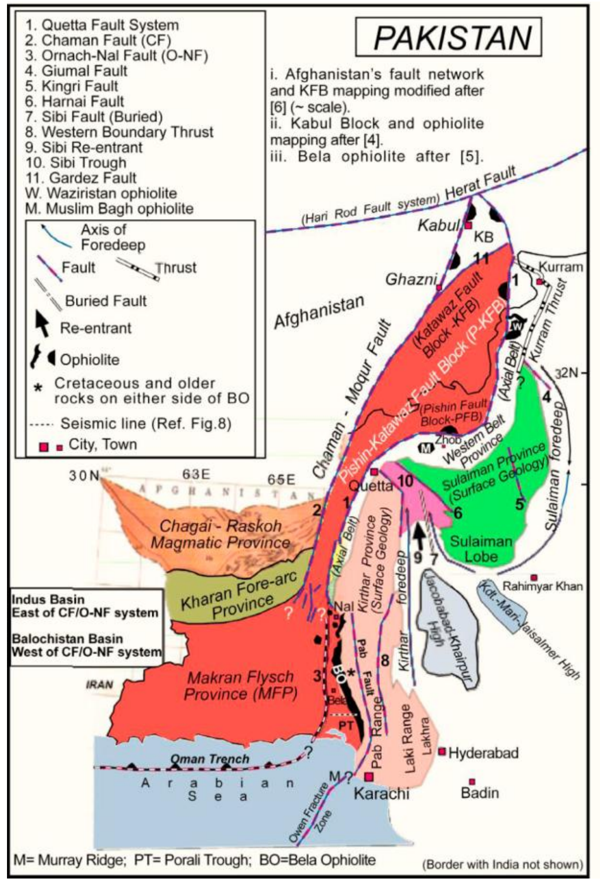

Figure 1. Basin architecture and the Geological Provinces (GPs) of western part of Pakistan, excluding their continuation under the plains. Chaman and the Ornach-Nal Faults System mark the border between Balochistan Basin to its west and Indus Basin to the east. The Pishin–Katawaz Fault Block (P–KFB) is sandwiched between the Quetta Fault System (QFS) and the Chaman-Moqur Fault, having a geological continuity with the Makran Flysch Province. The QFS represents the limit of the western margin of the continental crust of the Indian Plate - the Indus Basin. Axial Belt, therefore, is renamed as Western Belt Province (WBP) belonging to the Indus Basin. The P–KFB is interpreted to represent segmented oceanic/transitional crust related to the NW margin of the Indian Plate. The southern extension of the WBP, through PT, is interpreted to be restricted along the Bela ophiolite. The Porali Trough (PT), a product of anti-clockwise rotation of Indian Plate, and P–KFB a product of converging microplates are interpreted to be analogues, where similar Eocene-Miocene sediments were deposited on the subducting oceanic/transitional crust of the Indian Shield with possible presence of ophiolite in between, along an inferred tectonized contact. The P–KFB and the Porali Trough are considered to represent marginal zones of the Indus Basin. Refer to Figure 8 for a geoseismic section across the Porali Trough (after Siddiqui, 2009). Tectonic Map of Pakistan (Kazmi and Rana, 1982) is used as a base for delineating the GPs. NTB & RT after Shah, 2009).

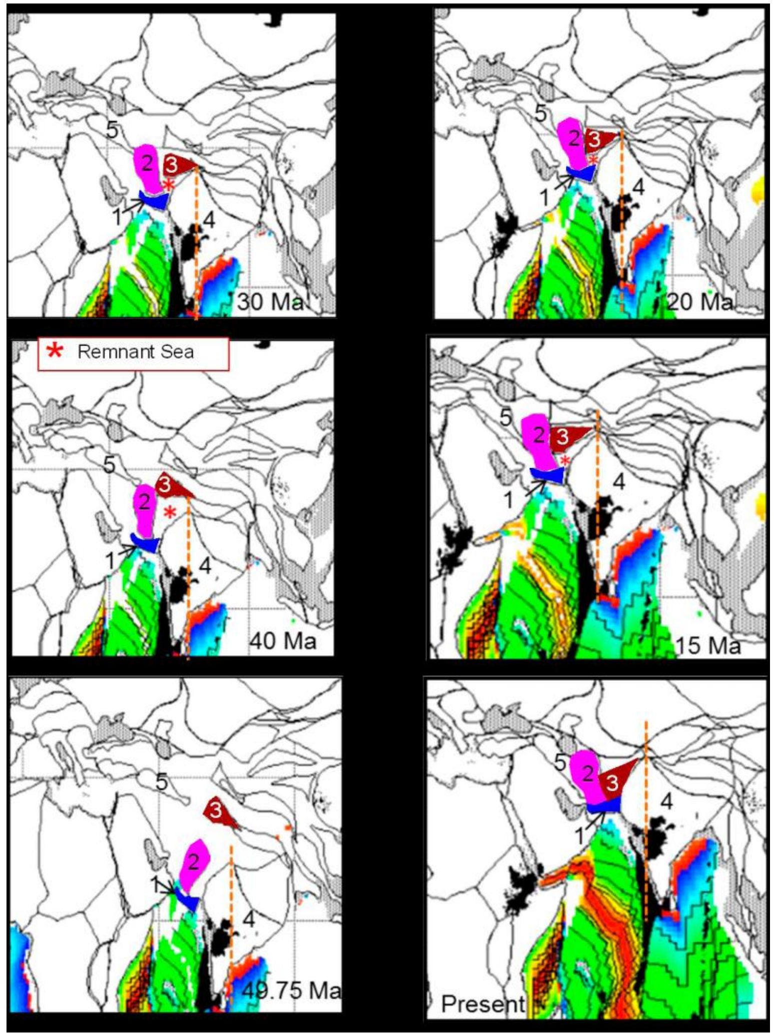

Figure 2. A combination of six sequential snap-shots from the animation of the drifting tectonic plates. The proposed Pak-Iran Makran microplate (P–IMM), the eastern part of which represents the Makran Accretionary Prism in Pakistan, independently kept pace with the northward drift of the Indian Plate, and the other microplates. The Remnant Sea that was initiated around 40 Ma provided a depositional trough for the future Pishin–Katawaz Fault Block (P–KFB). Due to the converging plates, the sea gradually shrank that compressed and elongated the Eocene-Miocene deposits of the P-KFB as shown in Figure 6. The dashed line highlights the anti-clockwise rotation of the Indian Plate. Only three of the microplates, which eventually were juxtaposed and coalesced with the Indian Plate to close the Remnant Sea, are colour-coded. Microplates 1, 2, 3 and 5 are part of the Eurasian Plate. (Modified after Siddiqui, 2012a). (1. Pak–Iran Makran microplate; 2. Central Iranian/Lut microplates; 3. Afghan microplate; 4. Indian Plate; 5. Zagros) (Snap-shots reproduced, with thanks, after obtaining permission of Shell International).

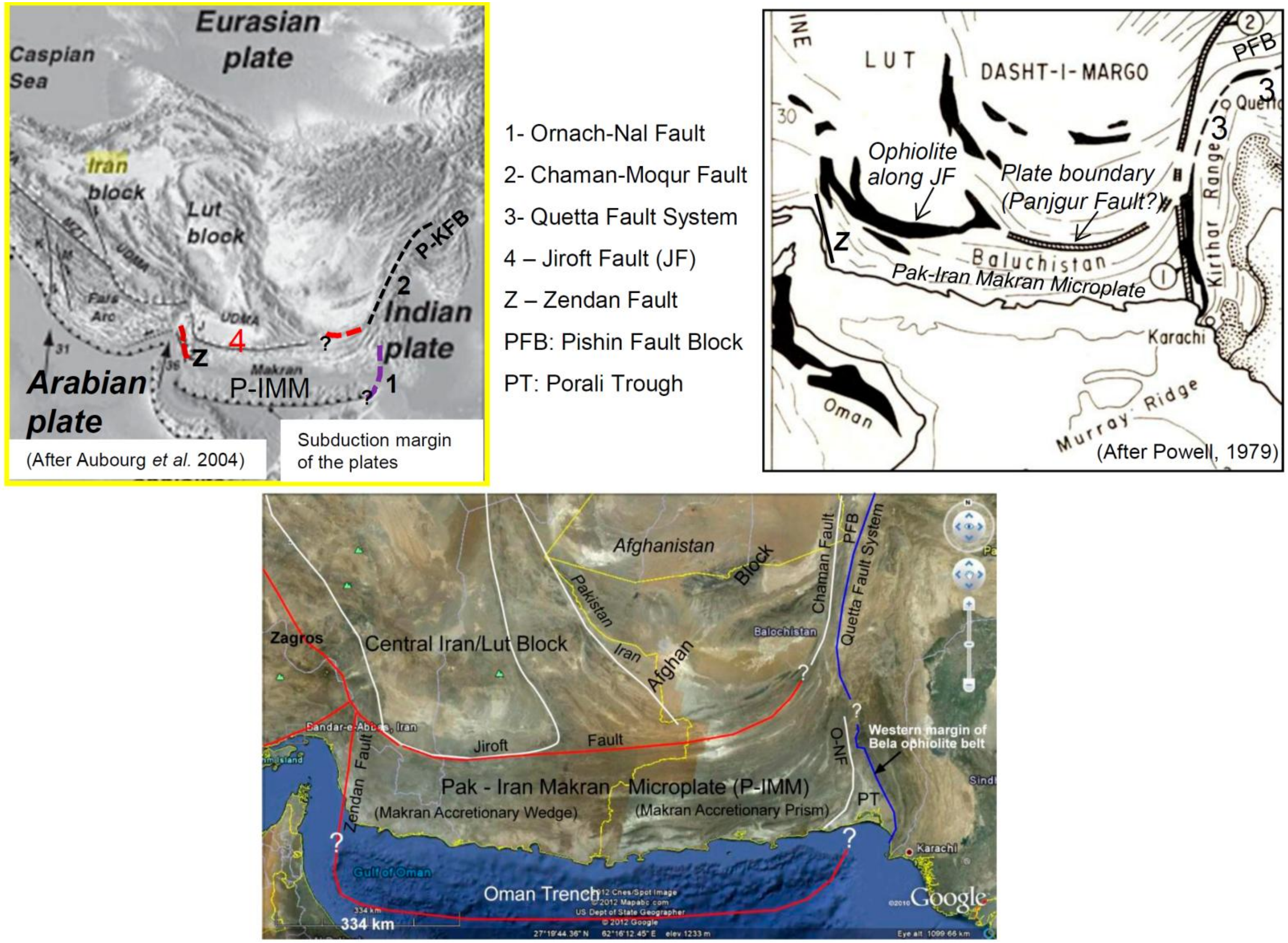

Figure 3. A simplified interpretation of Google Earth image, and a Geodynamic map (top left) of Iran and surrounding countries. Between the subduction margin of Arabian Plate (Oman Trench) and the Jiroft Fault lies the proposed Pak–Iran Makran Microplate (P–IMM), which is bounded by the Zendan Fault (Z) in west and the Ornach-Nal Fault in the east. P–IMM is interpreted to be in geological continuity with P-KFB (refer to Figure 1 and Figure 6). Inset on top right shows the westward turning of the Chaman Fault (2), which coincides with the plate boundary and likely to be in continuity with the Jiroft Fault (4), Section 'i' and 'ii' represent Figure 4C and Figure 7E, respectively. (Source: Google Earth; Geodynamic map modified after Aubourg, et. al. (2004); Top right annotated after Powell (1979). (PT=Porali Trough; PFB= Pishin Fault Block; P–KFB= Pishin–Katawaz Fault Block; O–NF= Ornach–Nal Fault, 3= Quetta Fault System).

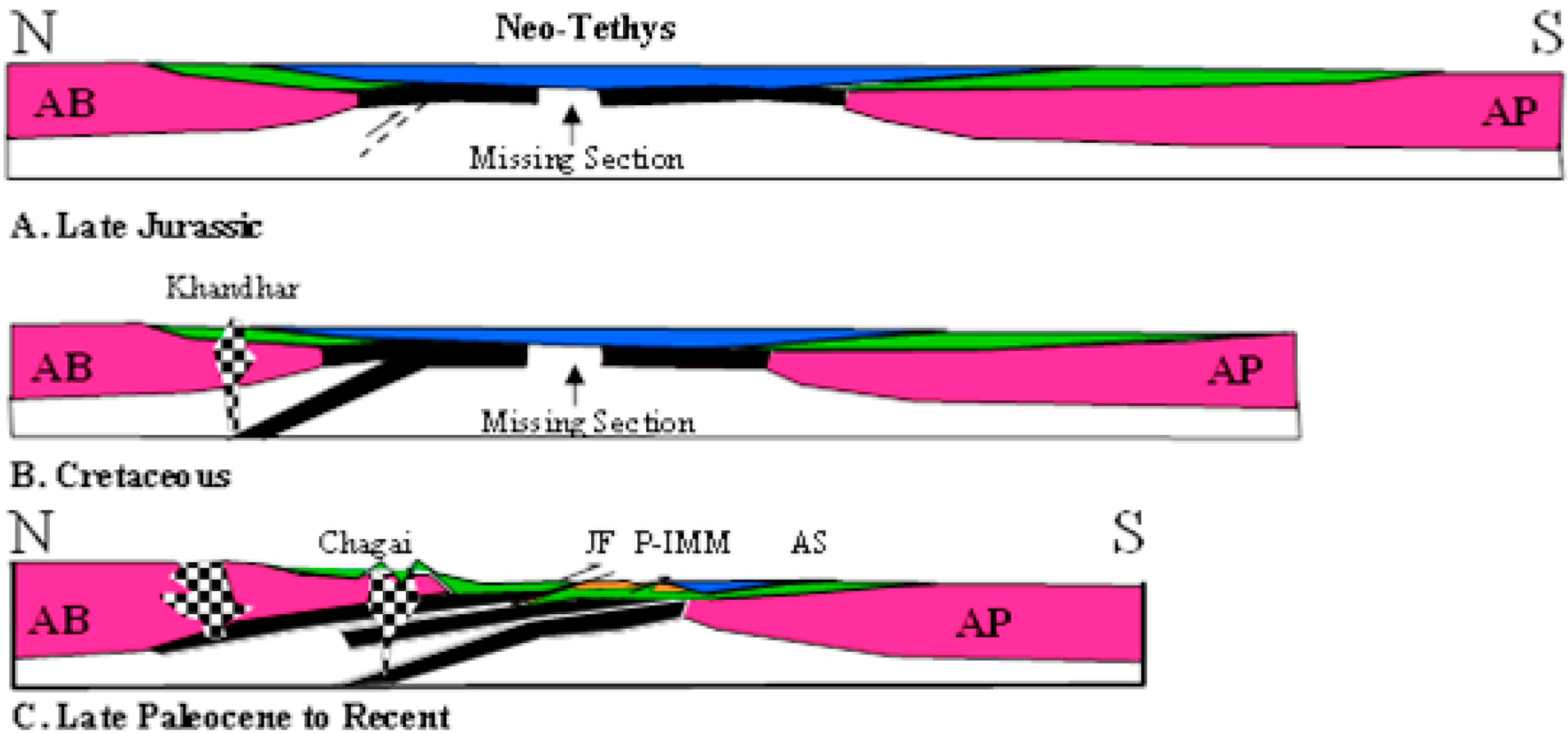

Figure 4. A kinematic model inferring the tectonic development along the Makran convergence zone. Missing section represents the uncalculated amount of Neo-Tethys that is recycled (shortened) due to collision and subduction. See text for details and Figure 3 for location of section 4C. (AB = Afghan Block, AP = Arabian Plate; AS = Arabian Sea).

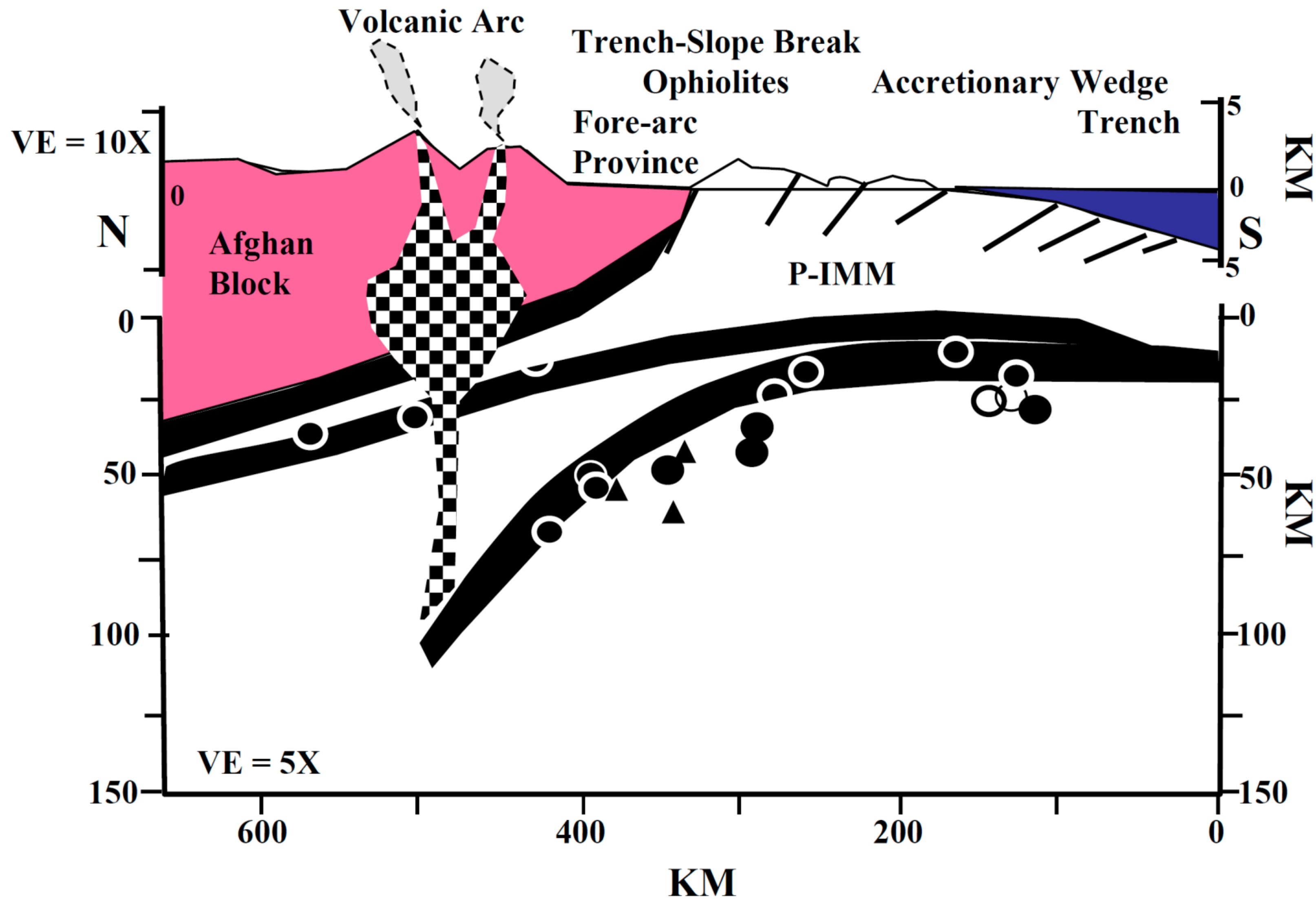

Figure 5. Tectonic model of the Makran convergence zone with depiction of Afghan Block, inferred Pak-Iran Makran Microplate (P-IMM), and present day Makran subduction zone. Afghan Block and P-IMM represent accreted terrains whereas active subduction is represented under-plating of oceanic crust related to the Arabian Plate below the Eurasian Plate. P-IMM in the model is represented by an oceanic lithosphere and Makran accretionary wedge. Solid circles and triangles represent the hypocenter of earthquakes of magnitude 4-5 and 6-7, respectively (modified from Jacob and Quittmeyer (1979).

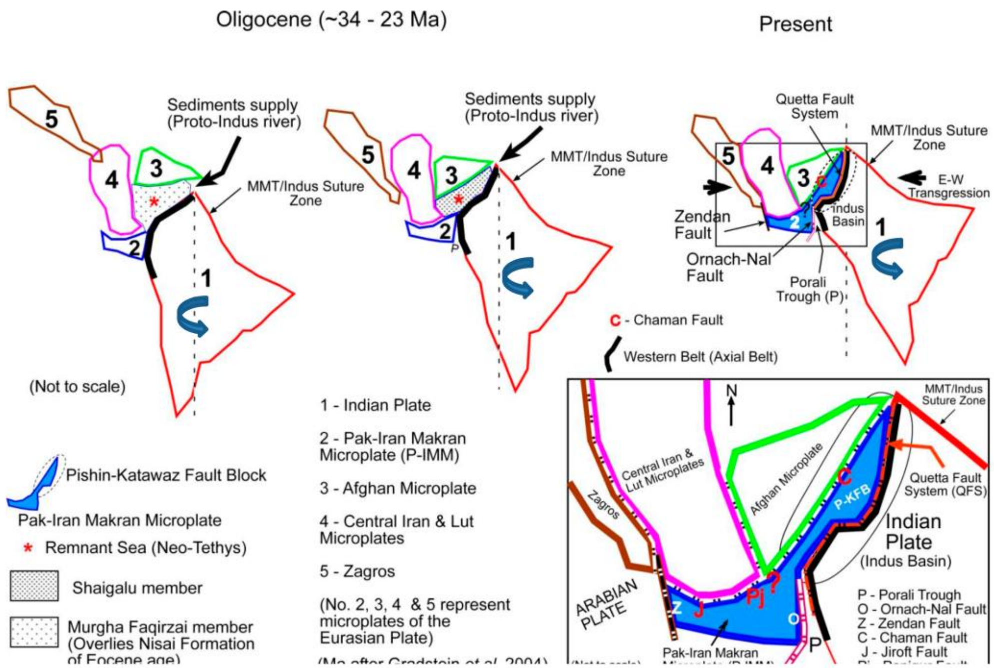

Figure 6. A simplified model for the evolution of the proposed Pak–Iran Makran Microplate (P–IMM), Pishin–Katawaz Fault Block (P–KFB) and the Western Belt (Ex-Axial Belt). Note the inferred changing shapes and the orientations of P-KFB and the Western Belt over geological time. The shapes and orientations of the P-KFB and the Western Belt changed in response to the Indian Plate's (IP's) drifting path and the converging microplates. The post-Miocene E–W compression resulted in the present day structural configuration. The subduction zone between Indian Plate and the Eurasian Plate provided the trough for the 'Remnant Sea' (Neo-Tethys) from Eocene onwards where initially Nisai limestone (Eocene) was deposited. It was followed by the huge detritus influx brought by the Proto-Indus River flowing into the trough from the northeast, which deposited the Khojak Formation (mainly Oligocene) in deltaic environments -- the present day P-KFB. The trough probably had an opening towards the SW where the P–IMM was converging, and hence the P-KFB maintained a geological continuity with the P–IMM, where flysch sediment supply from the tributaries of the river continued on top of the Eocene Nisai Limestone. These Cenozoic sediments were also deposited on the leading margin of the Indus Basin to develop into the so-called 'Axial Belt', which is proposed to be renamed as the Western Belt (WB), instead. WB was, thus, evolving at the collisional margin of the Indus Basin as the sedimentary strata was detached from the crystalline basement. The anti-clockwise rotation of the IP played a major role in the gradual widening of the Porali Trough synchronized with the deposition of the Cenozoic sediments similar to Pishin area. The vertical dashed line highlights the anti-clockwise rotation of the IP. The author prefers the westward turning of the Chaman Fault (after Powell, 1979) to join with the E–W running Panjgur Fault (?) in Pakistan and Jiroft Fault in Iran, both of which mark the northern boundary of the P-IMM (Figure 3). The rectangle in the upper right cartoon marks the location of the enlarged sketch shown below. Note that the Quetta Fault System is not joined with the Ornach-Nal Fault, but probably follows the western margin of the Western Belt (after Siddiqui, 2012b). (Digitized snap-shots from the animation of drifting tectonic plates by Shell International).

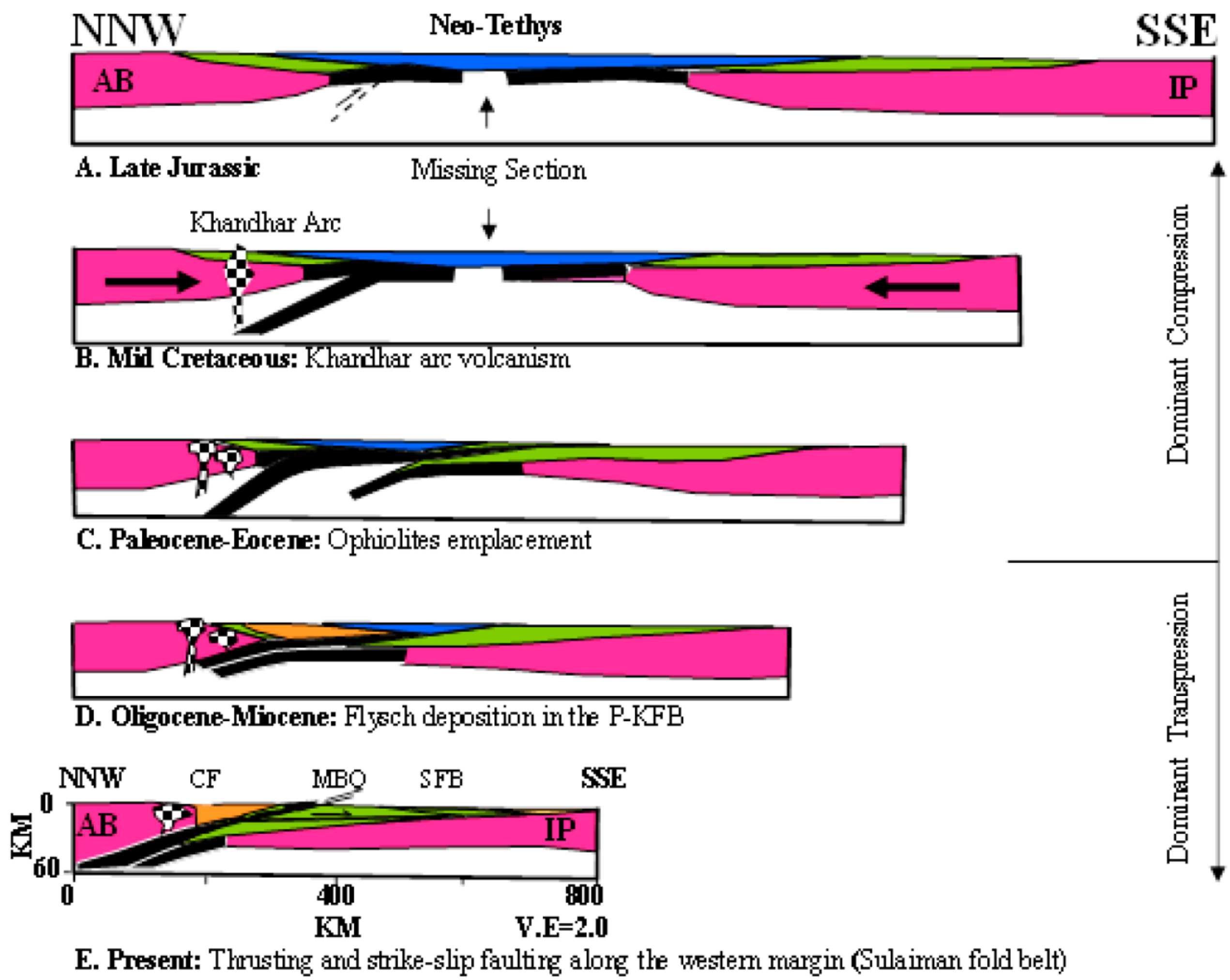

Figure 7. A kinematic model inferring the tectonic development across the western margin of the Indian Plate (IP) and the Afghan Block (AB). Notice presence of a subduction zone in the Mid-Cretaceous with Khandhar arc volcanism and inference of its shift towards south with emplacement of ophiolites in Paleocene (C). The segmented oceanic crust between the Chaman fault (CF) and Muslimbagh ophiolites (MBO) is interpreted to constitute the P-KFB that served as a syn-deformational basin for deposition of flysch deposits in Oligocene to Miocene (D). Onwards collision has led to the closure of basin, thrusting, and strike-slip faulting due to transpression along the Chaman fault and the western margin (E). About 353 km of orogenic contraction in the Sulaiman fold belt (SFB) is calculated by section balancing (23). The model is based on seismic interpretations and gravity modeling (4). Missing section represents the uncalculated amount of Neo-Tethys, which is recycled (shortened) due to collision and subduction. See Figure 3 for location of section 7E.

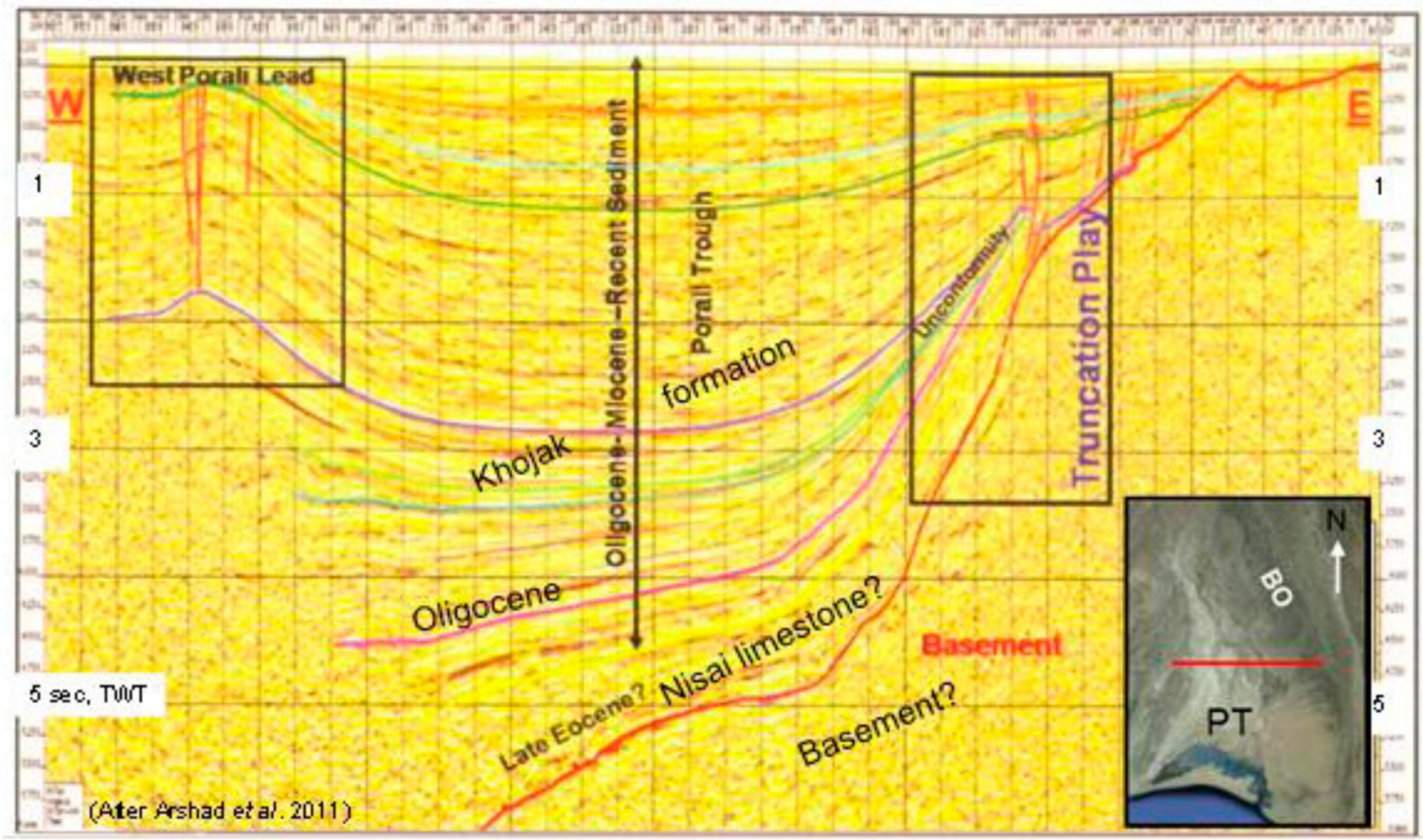

Figure 8. A geoseismic section (2D, # L99bn-04) along a dip-line across the Porali Trough (PT). Location of the cross-section is represented by the red line in the Inset. The trough seems to be an analogue of PKFB, with postulated similar deposition of rocks (Eocene/Oligocene/Miocene) in a tongue of closing Tethys Ocean between obliquely converging plates, with the emplacement of Bela Ophiolite (BO), similar to Muslimbagh and Zhob. The interpretation of basement, with opaque reflectors, below Eocene in the central part of the section and at/near to the surface in the eastern part is arbitrary, as this is not supported by the surface geology, with outcrops of Mesozoic strata on either side of the Bela Ophiolite (Figure 1). Alternately, the opaque seismic reflection may be related to a complex deformation due to transpression.