Probable existence of a Gondwana transcontinental rift system in western India: Implications in hydrocarbon exploration in Kutch and Saurashtra offshore: A GIS-based approach

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The Gondwanaland assembly rifted dominantly during Late Carboniferous–Early Permian forming several intracratonic rift basins. These rifts were subsequently filled with a thick sequence of continental clastic sediments with minor marine intercalations in early phase. In western part of India, these sediments are recorded in enclaves of Bikaner–Nagaur and Jaisalmer basins in Rajasthan. Facies correlatives of these sediments are observed in a number of basins that were earlier thought to be associated with the western part of India. The present work is a GIS based approach to reconnect those basins to their position during rifting and reconstruct the tectono-sedimentary environment at that time range. The study indicates a rift system spanning from Arabian plate in the north and extending to southern part of Africa that passes through Indus basin, western part of India and Madagascar, and existed from Late Carboniferous to Early Jurassic. Extensions related to the opening of Neo-Tethys led to the formation of a number of cross trends in the rift systems that acted as barriers to marine transgressions from the north as well as disrupted the earlier continuous longitudinal drainage systems. The axis of this rift system is envisaged to pass through present day offshore Kutch and Saurashtra and implies a thick deposit of Late Carboniferous to Early Jurassic sediments in these areas. Based on analogy with other basins associated with this rift system, these sediments may be targeted for hydrocarbon exploration.

Keywords. Permo-Triassic; transcontinental rift system; western India; GIS approach.

1. Introduction

During the Late Carboniferous to Lower Jurassic time, the Gondwana assembly of plates underwent major rifting in multiple stages (Langhi and Borel 2005; Metcalfe 2011; Ziegler 2015 and many others). This developed several intracratonic rift basins filled with dominantly continental clastic sediments. Such exposures of Gondwana sediments are found to occur in the central and eastern parts

of India, and had been studied in detail (Casshyap 1979; Casshyap and Tewari 1988; Tewari 1998; Bhattacharya *et al.* 2012; Bhattacharya and Bhattacharya 2015 and many others). In western India, similar correlative deposits occur as outcrops and subcrops in Bikaner–Nagaur and Jaisalmer basins of Rajasthan (figure 1a).

In this study, a GIS based approach is used as a plate reconstruction exercise. This attempts to move and rotate themes representing constituent

plates of the Gondwana assembly and their inherent structural and stratigraphic elements to their initial position prior to rifting. This forms a novel attempt to reconnect the Late Carboniferous to Early Jurassic sediments of western India with their facies correlatives in terrains of Eastern Africa, Madagascar, Seychelles, Indus Basin and parts of Arabian peninsula of erstwhile associated plates. Based on this correlation, the tectono-sedimentary conditions at that time have been reconstructed. During this time, the western part of the Indian plate was associated with Seychelles–Madagascar, Africa and Arabian peninsula plates, whereas in the eastern part, it was associated with the Antarctic and Australian plates (figure 1b, reviewed in [Misra and Mukherjee 2015](#); also see [Misra et al. 2014, 2015](#); [Mukherjee 2017](#)). The northern part was a passive margin open towards the Paleo-Tethys at least since Cambrian ([Stampfli and Borel 2002](#)) with a number of microcontinents such as Iran, Lut, Lhasa, Karakoram, Sistan-Helmand, Sibumasu positioned across the Paleo-Tethys ([Torsvik and Cocks 2013](#)). This plate assembly was positioned in the polar region during Late Carboniferous from where it migrated northward to near equator at the end of Triassic ([Scotese et al. 1999](#), [Torsvik and Cocks 2013](#)). At the end of the Pan-African Orogeny in Early Cambrian, all these continents co-existed as Pangaea supercontinent. This plate assembly underwent a general crustal extensional regime in Late Carboniferous and Early Permian producing broadly N–S rifts, which, apparently, also preceded the onset of Gondwana’s breakup ([Delvaux 1991](#)). This paper forms a novel attempt in which, Late Carboniferous to Early Jurassic facies equivalents and associated structural elements in western India and associated plates, as described in existing literature, are analyzed and rotated in a GIS framework to fit their plate tectonic template in the corresponding age. This GIS based exercise helps to bring out new insights into the existing plate tectonic model. The effects and implications of this new model form the principal focus of the study.

2. Late Carboniferous–Permo-Triassic facies equivalents of associated plates

A concise account of the tectonic layout and sedimentary succession of Lower Gondwana sediments in contiguous basins during that time period is

described as it forms the basic data of the present study. These sedimentary deposits are described in terms of gross lithology and their broad environment of deposition as represented in existing knowledge base. These are then correlated with each other to draw a conclusion about their relationships if any.

2.1 Karoo deposits of East African basins

The sediments deposited in Late Carboniferous–Permian rifts in the East African countries of South Africa, Kenya, Tanzania and Mozambique are mostly referred to as the Karoo System.

South Africa: In the main Karoo Basin in South Africa (figure 5), the Karoo sequence (figure 2) is subdivided into Dwyka Series (Late Carboniferous), Ecca Series (Early Permian), Beaufort Series (Late Permian–Early Triassic) and Stormberg Series (Late Triassic) ([Catuneanu et al. 2005](#)). Among these, the Dwyka Series consists of massive diamictites, varved shales and pebbly sandstones, products of glacial to fluvio-glacial deposition. Studies by [Herbert and Compton \(2007\)](#) indicate that fresh water lake environments also persisted during the deposition of these sediments. The Ecca Series consists of dark clastic sedimentary strata such as shale, siltstones, fine to very coarse, pebbly sandstones and coal. These are inferred as marine to deltaic to fluvio-lacustrine deposits ([Uys 2007](#); [Nyathi 2014](#)). The Beaufort Group is terrestrial and consists of lighter coloured mudrocks, sandstones and occasional conglomerates representing predominantly overbank (backswamp and levee splay) fluvial deposition accumulated sub-aerially under oxidizing semi-arid to arid conditions on broad gently subsiding alluvial plains ([Smith et al. 1993](#); [Uys 2007](#)). Stormberg series consists mainly of sandstones and mudstones and indicates gradual desertification with westerly wind-dominated sedimentation ([Smith et al. 1993](#)).

Tanzania: The Karoo Basin system in Tanzania (figure 5) is a manifestation of the early stage of Gondwana break-up in east-central Africa ([Delvaux 2001](#)). The Karoo sequence here is represented by the Songea Group of rocks that range in age from Pennsylvanian to Anisian (lower Middle Triassic) and consists of six formations (figure 3), viz., Idusi, Mchuchuma, Mbuyura, Mhukuru, Ruhuhu, and Usili formations ([Wopfner 2002](#)). The lowermost Idusi formation is Late Carboniferous–Early Permian in age, deposited in a glacial

Figure 1. (a) Layout of Lower Gondwana outcrops and subcrops of India along with major tectonic elements. Four major trends of Gondwana rifts in the peninsular area are identified (1) broadly E–W Satpura, Son and Damodar Valley basins, (2) NNW–SSE Pranhita–Godavari Valley basin, (3) NW–SE Mahanadi Valley basin and (4) NNW–SSE trending Purnea–Rajmahal–Galsi basin (after Mukhopadhyay *et al.* 2010). The encircled areas show Gondwana outcrops and subcrops in western part of India. (b) Template of Gondwana Plate assemblage associated with the Indian Plate during Late Permian (after Smith *et al.* 1981).

Late Triassic to Mid Jurassic	Stromberg Series		Sandstones and mudstones	Gradual desertification
Late Permian	Beaufort Series		Mudrocks, sandstones and occasional conglomerates	Fluvial
Early Permian	Ecca Series		Shale, siltstone, fine to very coarse, pebbly sandstone and coal	marine to deltaic to fluvio-lacustrine
Late Carboniferous	Dwyka Series		Diamictites, Varved shales and Pebbly Sandstones	Glacial to fluvio-glacial

Figure 2. A generalized stratigraphy and depositional environment of main Karoo Basin in South Africa (after Catuneanu *et al.* 2005). The legends are discussed in figure 11.

Lower to Middle Triassic	Manda Beds		Mudstones interbedded with sandstones & grits	Fluvio-deltaic
Upper Permian	Usili Fm.		Conglomerate, Sandstones & mudstones	fluvio-lacustrine
Middle Permian	Ruhuhu Fm.		mudstones, cherty siltstones and interbedded sandstones	fluvial to shallow lacustrine
Lower to Middle Permian	Mbuyura Fm.		Shale, sandstone and coal	Fluvial to Swampy
Late Carboniferous to Early Permian	Idusi Formation		Massive Tillites	glacial to euxinic lacustrine

Figure 3. A generalized stratigraphy and depositional environment of Gondwana deposits of Tanzania (after Wopfner 2002).

to euxinic lacustrine environment and composed of massive tillites (Wopfner and Diekmann 1996). The Idusi Formation is followed by a fluvial to swampy coal bearing Mchuchuma Formation (Krueser and Woldu 2010), and Mbuyura Formation of Early to Middle Permian age consisting of sandstones, shales and coal. This is subsequently followed upward by a Middle Permian Mhukuru Formation and Ruhuhu Formation consisting of mudstones, cherty siltstones and interbedded sandstones suggesting fluvial to shallow lacustrine environment (Semkiwa *et al.* 1998; Wopfner 2002). Further

in Late Permian–Early Triassic, the stratigraphy is represented by a fluvio-lacustrine Usili Formation constituted of conglomerates, sandstones and mudstones deposited due to an increased sediment load resulting from subsidence (Sidor *et al.* 2010). This is followed unconformably upward by desiccating cyclothems of fluvio-deltaic Manda Beds of Early to Middle Triassic (Behrensmeier and Hill 1988; Wopfner *et al.* 1991; Wopfner 2002).

Madagascar: In western Madagascar, sediments of the Karoo Supergroup were deposited in the

Figure 4. (a) A generalized stratigraphy and depositional environment of Morondova basin of Madagascar (after Schandelmeier et al. 2004). (b) Stratigraphy envisaged in Seychelles after USGS 2012.

Morondova Basin (figure 5). The Sakoa Group are the oldest rocks in the Morondava Basin, consisting of Late Carboniferous–Early Permian tillites, overlain by Early Permian coal-bearing horizons and redbeds, and Middle Permian marine limestones. The Sakamena Group, which unconformably overlies the Sakoa Group, comprises Late Permian sandstones and conglomerates deposited by braided streams followed by Early Triassic alternating sandstones and shales deposited in low gradient meandering streams and in shallow lakes with marine influences. The Middle Triassic to Early Jurassic Lsalo Group (figure 4a) in turn unconformably overlies the Sakamena Group, and consists of continental sandstones deposited by braided streams (Wescott and Diggins 1998; Schandelmeier et al. 2004).

Seychelles: In Seychelles, though only four wells had been drilled with the deepest well Reith Bank-1 penetrating down to Middle Triassic, Late Carboniferous to Permian stratigraphy had also been envisaged (figure 4b), which constituted with shales and sandstones deposited in a fluvial environment with marginal marine influences (after USGS 2012). As per Plummer and Belle (1995) the late Early Jurassic is characterized by a series of cyclical sandstones and shales representing continuing rift sequence deposited by meandering rivers.

Somalia and Ethiopia: In Somalia, the Mugudh Basin or the Somali Embayment shows outcrops of Adigrat Sandstone (figure 5) characterized by three stratigraphic units: a lower sandy conglomerate, middle shale with boulders and upper sandstone believed to be of Early Jurassic age deposited

Figure 5. Map depicting the layout of Gondwana formations of the eastern part of African plate, Madagascar and Seychelles along with major structural features (redrawn after Delvaux 1991; Accordi and Carbone 2000; Collins and Windley 2002; Catuneanu *et al.* 2005; Kumpulainen *et al.* 2006 and Petroseychelles 2013).

in a fluvial equivalent environment (Selley 1997). In the adjoining Ogaden basin in Ethiopia, the stratigraphic sequences consist of a Late Carboniferous to Early Permian Calub Formation consisting of sandstone and conglomerates deposited in a glacio-fluvial environment. It is followed upward by Middle to Late Permian Bokh Shale consisting of carbonaceous shales deposited in a lacustrine environment. The Bokh Shale is succeeded by a Triassic Gumburo Shale characterized by black shales and sandstones of fluvial environment, which

is overlain by the Adigrat Formation consisting of conglomerates and sandstones deposited in a fluvial environment (Ahmed 2008).

2.2 Late Carboniferous–Permo-Triassic deposits of eastern Arabian peninsula

Oman: The Late Carboniferous to Permo-Triassic sediments of the Hausi Group host major hydrocarbon reservoirs in the Oman Interior Basin. This clastic sequence is composed of glacio-fluvial to

glacio-lacustrine deposits of the Al-Khlata Formation, which consists of a complex package of clastic lithologies that range from conglomerates through diamictites, gravels, pebbly sandstones, siltstones to silty shales (Wang *et al.* 2011; Heward and Penney 2014). These are overlain by fluvial dominated Gharif Formation (Abbasi *et al.* 2013) constituted of sandstones and clays deposited by low sinuosity braided streams (figure 6a). Both of these comprise the Haushi Group and are important hydrocarbon reservoirs throughout Oman. This is followed by a Khuff Formation consisting of an alternation of carbonate and siliciclastic deposits resulting from a major marine incursion in the Arabian plate (Al-Aswad 1997; Pollastro 1999). In the Oman Mountain area, which is the margin of the Arabian continental platform, Late Permian to Mid-Cretaceous is represented by Hajar Supergroup constituted predominantly of marine carbonates. The base of this Hajar Supergroup is marked by meter to decameter-thick sequence of Middle Permian clastic and volcanoclastic rocks (Chauvet *et al.* 2009) associated with pelagic sediments (figure 6b).

2.3 Late Carboniferous–Permo-Triassic of western part of Indian plate

In the Indian plate, most of the Gondwana deposits occur in peninsular India. These deposits range in age from Late Carboniferous to Lower Cretaceous and are presently oriented along four major linear belts (figure 1a) namely (1) ENE–WSW trending Satpura and Son Valley basins and E–W to WNW–ESE trending Damodar–Koel Valley basins (2) NNW–SSE trending Wardha–Pranhita–Godavari Valley basin (3) NW–SE trending Mahanadi Valley basin that swerves to WNW–ESE direction in southernmost Talcher coalfield and (4) NNW–SSE trending Purnea–Rajmahal–Galsi basin belt (Mukhopadhyay *et al.* 2010). Deposition in the Gondwana basin initiated with glaciogenic Talchir Formation followed by coal bearing Karharbari Formation deposited by braided streams and succeeding Barakar Formation by meandering streams in rifted valleys. These coal bearing sequences were followed by a fluvial barren measures characterized with a gap in coal deposition that resumed again in the Late Permian in the form of Raniganj Formation deposited from the meandering streams. In the Early to Middle Triassic (Panchet/Kamthi/Bhimaram formations), feldspathic sandstone with red beds devoid of coal were deposited by braided

streams (Casshyap and Tewari 1988; Veevers and Tewari 1995). Supra-Panchets consisting of coarse grained sandstones and conglomerates were deposited by braided channels in Late Triassic after a renewed phase of fault movement. Deposition ended during an Early Jurassic transpression that dismembered the lobate master basin into individual structural basins (Veevers and Tewari 1995). Equivalent deposits occurring as isolated deposits in the extra-peninsular part of Indian plate in the western extremities are discussed as follows:

Indus Basin: In the Indus Basin, the Late Carboniferous–Permo-Triassic succession is mainly exposed in the Salt Range, Surghar and Marwat-Khishor area of Upper Indus Basin; whereas it occurs as subcrops in Middle Indus Basin in Pakistan (figure 7b). This sequence is divided into three groups representing different depositional settings. The largely continental succession is represented by the Nilwahan Group and is the bottommost. The shallow marine Tethyan succession is represented by the overlying Zaluch Group (Jan *et al.* 2009). This is then succeeded by the Triassic Musa Khel Group with both clastics and carbonates (figure 7a).

In the Nilwahan Group, the oldest deposit is represented by the Early Permian Tobra Formation, glacio-fluvial (Ghazi *et al.* 2012) in origin consisting of conglomerates, sandstones, siltstones and shales that is considered equivalent to the middle part of the Al Khlata Formation of south Oman (Jan and Stephenson 2011). This is followed upward by Early Permian deposits of Dandot Formation of a marginal marine environment (Ghazi *et al.* 2012), Warchha Formation of a meandering fluvial origin (Ghazi and Mountney 2010) and Sardhai Formations of a dominantly fluvial origin with lagoonal and marine influences.

The Nilwahan Group is followed upwards by the Zaluch Group consisting of Late Permian Formations of Amb, Wargal and Chhidru (Jan *et al.* 2009). This Group has well-exposed succession of the shallow marine to inter-tidal carbonate facies of the Amb, Wargal and Chhidru Formations. The Middle Permian Amb Formation is composed of sandy limestones, sandstones, and subordinate pelites of a shallow marine environment (Aadil *et al.* 2013). This is followed upward by the Wargal Formation, composed of pure limestones with subordinate dolomites and marls indicating carbonate platform in shallow marine reefal environment (Ezaki 2006). The Chhidru Formation shows a

Figure 6. (a) Generalized stratigraphy of Lower Gondwana in Oman (after Abbasi *et al.* 2013). (b) Map depicting the layout of Gondwana formations in the eastern part of Arabian peninsula, especially Oman along with N–S to NNE–SSW structural features (redrawn after Lapierre *et al.* 2004; Naji and Janardhana 2009 and Chauvet *et al.* 2009).

continuous terrigenous input and freshwater inflow (Ezaki 2006) to the basin represented by grey calcareous sandstones, along with infrequent limestones and shale beds and is considered to be near

shore to a sublittoral environment (Khan and Afzal 2005).

This is followed upward by the Triassic Musa Khel Group consisting of Mianwali, Tredian and

Figure 7. (a) Generalized stratigraphy of Lower Gondwana in Indus Basin (after Khan *et al.* 1986; Ghazi *et al.* 2012). (b) Map depicting layout of Permo-Triassic Gondwana formations as outcrops and subcrops in Indus Basin, Pakistan along with structural layout of relevant faults (after Kusky *et al.* 2005; Raza *et al.* 2008; Aadil and Sohail 2011; Ghazi *et al.* 2012; Hasany *et al.* 2012).

Kingriali Formation. The Mianwali Formation consists of limestones, marls, sandstones, siltstones and dolomites suggesting a shallow marine to pro-delta environment (Iqbal *et al.* 2013). The overlying Tredian Formation of Middle Triassic is constituted of micaceous sandstones with interbedded shales suggesting a delta plain/fluviial setting with dominant fluviial character (Iqbal *et al.* 2013). Further upwards the Kingriali Formation of Late Triassic is constituted of dolomitic limestones of a shallow marine origin deposited in shelf conditions (Wandrey *et al.* 2004). The Kingriali Formation is also referred to as Wulgai Formation occurring as subcrops in Axial belt region of Pakistan (after Ghazi *et al.* 2012 and Khan *et al.* 1986). In Well

Marvi-1 in Punjab platform, south Indus Basin, traps with a Permian age had been observed along with Permian sediments (figure 7b).

Bikaner-Nagaur and Jaisalmer Basin: In western India, outcrops of Lower Gondwana age present in Bikaner-Nagaur Basin, Rajasthan are represented by Bap and Badhaura Formation. The Bap Formation is composed of boulder clays with pebbles of rhyolites, granites, limestones and varved clays suggesting a Lower Permian–Carboniferous age and a fluvioglacial environment with marine influence (Shah and Mehrotra 1985). In the overlying Badhaura Formation (figure 8a), the Permian deposits constitute medium-to-coarse grained sandstones with calcareous shales suggesting a shallow

Figure 8. (a) A generalized stratigraphy and depositional environment of Bikaner–Nagaur and Jaisalmer Basins (after Mishra *et al.* 1961; Lukose and Misra 1980; Shah and Mehrotra 1985; Misra *et al.* 1996; Singh 2006). (b) Layout of Late Carboniferous–Permian–Triassic–Early Jurassic formations in western India (after Singh 2006; Chauvet *et al.* 2008; Shellnutt *et al.* 2012; Raju *et al.* 2014).

marine environment based on ichnofossil studies by Kulkarni and Bokar (2014). Subcrops of Bap and Badhaura formations are encountered in wells like Ba drilled by OIL and Pu by ONGC in Bikaner–Nagaur Basin (figure 8b). An Early Permian (Asselian–Sakamarian) age has been inferred for Bap and Badhaura Formation based on biostratigraphic studies (Venkatachala and Rawat 1984; Prasad *et al.* 2010).

In the adjacent Jaisalmer Basin, though no outcrops of Permo–Triassic had been mapped, subcrops of Late Permian to Triassic Bhuana Formation had been encountered in a number of wells like Mi-1, Bh-1 and Lu-1 in the Miajlar sub-basin drilled by ONGC (figure 8b). The Bhuana Formation is characterized by reddish, coarse grained,

non-calcareous, feldspathic sandstones with intercalations of ferrugeneous claystones (figure 8a; Singh 2006). As per palynostratigraphic studies carried out by Lukose and Misra (1980) and Misra *et al.* (1996), the lower part of the subcrops is dated Late Permian in age; whereas the upper part are Late Triassic with a hiatus in between. The basal part of the Permian sediments are shallow marine, the upper part of the Permian sequence and basal part of Triassic are non-marine regressive. The sequence immediately overlying the basal part of Triassic is again shallow marine indicating transgression. The top part of it is again non-marine suggesting regression (Singh 2006). The Bhuana Formation is conformably overlain by Lathi Formation comprising of coarse-to-medium grained sandstones with interbeds of shales/claystones and occasional lignite. The thickness of the formation is found to increase in the northern and western part of the basin. Based on biostratigraphic data, Lathi Formation is believed to be of Liassic age deposited in a fluvio-deltaic environment (Singh 2006).

Besides, an outcrop of Panjal volcanics in Kashmir Himalayas (figure 8b) represents a thick sequence of effusive basaltic rocks intercalated with Tethyan sediments with an age of Late Sakmarian of Early Permian (Shellnutt *et al.* 2012). Undated volcanics of probable Gondwana affinity has also been encountered below Lower Cretaceous formations in ONGC well Lodhika-1 in Saurashtra. Reworked Carboniferous palynomorphs have also been reported from the basal clastic sediments in the Panna Formation (Paleocene–Early Eocene) in Mumbai Offshore (Mehrotra *et al.* 2001).

3. Reconstruction and analysis

All these above facies equivalents of Late Carboniferous–Permo–Triassic in terms of outcrops and subcrops encountered in western India and erstwhile associated plates are plotted in a GIS platform using ArcGIS 10.3. These along with the associated faults are rotated to fit their position in Late Carboniferous–Early Jurassic (figure 9) as per the template described by Smith *et al.* (1981).

These GIS-based themes of outcrop and subcrops when rotated back to their Late Carboniferous–Early Permian position based on the template described in figure 1(b) display an almost linear disposition of Dwyka Formation of South Africa, Sakoa Formation of Madagascar, subcrops

Figure 9. Flowchart depicting methodology followed in the GIS-based reconstruction.

of Nilahwann Group in Indus basin and the Al-Khalata and Gharif formations in Oman for about 6500 km (figure 10a). Almost in all these deposits, the basal sediments are glacial debris-flows. The faults associated with these deposits also exhibit a parallel trend to these formations and display an apparent continuity. One of the possibilities arising out of these above GIS-based observations involving continuity and similarity in the structural and lithological settings of Gondwana sediments is the probable existence of an embryonic rift that spanned from the end of South Africa through Madagascar, Saurashtra, Kutch, Rajasthan in India, Indus Basin in Pakistan up to the Arabian peninsula in the north. Since the axis of the rift houses the oldest sediments, Late Carboniferous–Early Permian sediments may be expected to occur along the proposed rift axis passing through Saurashtra offshore. These Carboniferous sediments supposedly aligned along the rift axis may serve as source to the reworked Carboniferous palynomorphs in adjacent Mumbai offshore where no Gondwana sediments have been encountered till date. Tectonic upheaval during Seychelles–India separation in Upper Cretaceous

may have resulted in the derivation of the palynomorphs from the initial Carboniferous sediments of the rift and their subsequent re-deposition in Paleocene–Early Eocene sediments of Panna Formation. As such, these palynomorphs strengthen the possibility of occurrence of the transcontinental rift. A few of the Carboniferous palynomorphs extracted from the Panna Formation resemble those encountered in the Late Carboniferous–Early Permian Haushi Group in Oman and Dwyka Group in Zimbabwe (Kumar 2010). This suggests a similarity in tectono-sedimentary environment in these three areas. One of the inferences of this observation is that these three areas may be connected through the proposed transcontinental rift at that time that spanned from northern Oman through offshore Kutch and Saurashtra Basin to the south of Africa. In such a case, this paleo-rift also forms the channel for transgression from Paleo-Tethys in the north to the southern part resulting in marine influences in Early Permian formations of Africa and Madagascar. This rift probably breached the tectonic barrier that limited the Cambrian Formations of the Arabian plate and western part of the Indian plate to the north (Pangtey *et al.* 2013). Permian volcanism encountered in well Marvi-1 in Lower Indus basin has been associated with the Thar Rift that has a parallel disposition to the transcontinental rift trend and is believed to have initiated during initial Gondwana rifting (Zaigham *et al.* 2012). Undated volcanics occurring non-conformably below the Early Cretaceous Formations are also encountered in well Lodhika-1 in Saurashtra falling in the rift trend (figure 10a). These volcanics may be a result of the plume activity that initiated the transcontinental rift in Late Carboniferous–Early Permian (figure 8b).

In the Middle Permian–Early Triassic, a GIS-based tectonic fit indicated that the transcontinental rift widened with its axis migrating westward (figure 10b). The most significant tectonic event in this phase was the opening of Neotethys Ocean, north of Indian plate (Torsvik and Cocks 2013). Thus, a string of Cimmerian terranes moved away from the previous Gondwana craton (Torsvik and Cocks 2013). This separation of the Cimmerian continents and the opening of the Neo-Tethys resulted in an NW–SE axis of extension north of Indian Plate at that time. This extension may be instrumental in the formation of a number of cross trends parallel to the extension axis, transverse to the transcontinental rift trend. One of the

Figure 10. (a) A GIS-based reconstruction of Late Carboniferous–Early Permian facies correlatives and associated faults using template by [Smith et al. \(1981\)](#) shows an overall alignment of outcrops, subcrops and structural feature. This alignment defines the incipient transcontinental rift. The reworked Carboniferous palynomorphs in Panna Formation, Mumbai High may be derived from the adjacent initial transcontinental rift sediments that had been exhumed during the tectonic upheaval leading to the Late Cretaceous separation of Seychelles. In the figure, 1. Main Karoo Basin, 2. Tanzania, 3. Morondova Basin, Madagascar, 4. Seychelles, 5. Bikaner–Nagaur Basin, 6. Indus Basin, 7. Oman. (b) A GIS-based reconstruction of Middle Permian–Early Triassic facies correlatives and associated faults indicate the rift getting wider in this phase. Structure contours at the base of Triassic (in inset) in Punjab platform, Indus Basin, Pakistan (after [Raza et al. 2008](#)) are found to be parallel to rift trend with evidences of development of cross trend in response to opening of Neotethys. The area marked with red dotted line is shown inset with structure contours. In the figure 1. Main Karoo Basin, 2. Tanzania, 3. Morondova Basin, Madagascar, 4. Jaisalmer Basin, India, 5. Indus Basin, Pakistan and 6. Oman. (c) GIS based reconstruction of Middle Triassic to Early Jurassic facies correlatives indicating a dominant fluvial system in the central part of the transcontinental rift spanning Jaisalmer, Kutch basin and Seychelles. Structure contour maps ([Raza et al. 2008](#)) in Punjab platform, Indus Basin and faults mapped on base of Jurassic sequence from seismic data in Kutch offshore ([Dash et al. 2015](#)) and Jaisalmer Basin are found to follow the rift trend. Lithological symbols described in figure 11.

cross trends may be the Lahore–Sargodha–Delhi basement ridge in northern Indus basin that was uplifted in Middle Permian ([Asim et al. 2014](#)).

This ridge may be instrumental in stopping marine incursion from the north resulting in a dominance of carbonate facies north of this ridge whereas

Figure 10. (Continued.)

southwards it is dominated by clastics with a predominant fluvial affinity (figure 11). The effect of the ridge as a barrier to transgression is evident from the palynostratigraphic studies (Lukose and Misra 1980 and Misra *et al.* 1996) in the pre-Lathi sediments in Jaisalmer basin. The studies indicate the upper part of the Permian sequence and basal part of Triassic as non-marine regressive sequence in contrast to the shallow marine sediments in basal Permian. Structure contour maps at the base of Triassic, of the Punjab platform in Indus Basin (Raza *et al.* 2008) rotated to their paleo-position in Triassic, display a parallelism in trends indicative

of a rift controlled deposition in the area. However, geometry of the structure contours straightway suggests cross trends (figure 10b, inset). One of the effects of the development of the cross trends may be that the longitudinal drainages that developed in the earlier undifferentiated rift draining the entire basin may be restricted in this phase limiting their drainage area. This may lead to a lithological variation in the rift that is significantly different from the uniformity in sedimentation of Early Permian (figure 11).

During Middle Triassic to Early Jurassic, GIS based analysis of the different facies correlatives

(c)

Figure 10. (Continued.)

indicate that dominant fluvial sedimentation in the transcontinental rift system may have continued without any major marine influences (figures 10c, 11). Palynostratigraphic studies (Saxena *et al.* 2016) record Late Triassic to Early Jurassic continental sediments in the well X-1 (figure 13a) in Saurashtra offshore with a good assemblage of spore-pollen. This closely resembles the assemblage from the two wells in B-2 and N-1 in Kutch onland drilled by ONGC (figure 8b) in western India recorded by Koshal (1984). The recorded assemblage is also correlatable with the Late Triassic sediments of Zaluch Group in Kohat–Potwar area (Mukherjee 2015); Shumerwali Formation in Jaisalmer Basin and Stormberg Group, South Africa (Saxena *et al.* 2016) suggesting connectivity even in this phase. Another well Y1 (figure 13a) in Kutch offshore is also reported to show an Early to Middle Jurassic

palyno-assemblage indicating a fluvial environment (Saxena *et al.* 2016). In the Kutch onland part, in Kaladonger Formation, though the lowest unit yields a nanofossil assemblage of Early Aalenian age, reworked nanofossils recovered from parts of it are indicative of a Lower Jurassic Pliensbachian–Toarcian age (figure 8b). Similarity has also been recorded between these reworked nanofossils recovered from Kutch basin and Late Pliensbachian age reworked nanofossils recovered from Masirah Island of Oman (Rai and Jain 2013). Structure and time contour maps of Late Triassic and Early Jurassic in Kutch and Saurashtra offshore, Jaisalmer basin, India and Punjab platform, Pakistan (Raza *et al.* 2008) in the Indian plate display structural development and subsurface morphology parallel to the transcontinental rift. Smaller faults mapped in seismic (Hasany *et al.* 2012; Raju *et al.* 2014) as

Figure 11. Sequence of sedimentary environments and broad lithologies in all basins discussed from south to north. Dominance of limestone and dolomite in the northern basins is observed whereas in the south, their correlative deposits are dominated by clastics resulting from fluvial sedimentation. Also the Late Carboniferous to Early Permian sediments show a uniformity in overall characters whereas lithological variation is significantly in the later sediments.

well as those on surface in these basins too conform these rift trends. This implies a rift related tectono-sedimentary setting continuing even in this phase. Grabens with small horsts in between had been mapped below Deccan Trap in the Jamnagar Dwarka area of the Saurashtra region by DSS studies with about 2500 m of sediments in them indicating such a setting (Pandey 2012).

The separation of the African plate from the Eastern Gondwana in Middle Jurassic probably marked the end of transcontinental rift setting with fluvial clastics getting replaced by marine carbonates. An overall lithological variation shows that the northern part of the rift depicts a dominant marine environment post-Permian whereas a dominantly continental environment dominated in the rest of the proposed rift from Jaisalmer–Bikaner–Nagaur basins in the north to the main Karoo basins in the south (figure 11).

4. Implications of the rift in hydrocarbon exploration

A number of hydrocarbon producing sedimentary basins are found to overlie the assumed rift. In the northern part, Al-Khalata and Gharif

formations in Oman act as a reservoir rocks for a number of oil fields (Bryant and Flint 2009). Similarly, in the Upper Indus Valley, Permian Tobra, Amb, and Wargal formations act as effective reservoir rocks for a number of producing fields like Adhi and Missa Keswal (Wandrey *et al.* 2004). In the southern part of the rift, heavy oil/tar sand had been discovered in Bemolanga and Tsimiroro in Isalo Formation in Madagascar and Ogaden Basin of Ethiopia is considered a proven petroleum basin producing from Calub and Adrigat sandstone (Boote and Matchette-Downes 2009). Oil seepages related to Adigrat sandstone in Somalia had also been observed (Southwestern Energy 2012). In Seychelles, Jurassic source rocks had been premised (Noskay 2012) based on geochemical studies on samples of well Reith Bank-1 (RB-1) attributing for its oil shows (figure 12). Migrated black oil is found in side-wall cores from the Karoo succession in wells drilled by Amoco with the same oil characteristics observed in numerous tar balls stranded around the many islands of the Seychelles archipelago.

All these imply the existence of a petroleum system within the rift system with the maturation aspect aided by heat related to the volcanics associated with rifting (Roberts *et al.* 2011). Also,

Figure 12. Hydrocarbon producing oil fields in different parts of the proposed rift with rift-related sediments. Well 1 in Saurashtra offshore may share a similar petroleum system making the area prospective. Green polygons and dots indicate oil fields and wells with hydrocarbon indications, respectively.

the shear heat/viscous dissipation (Mukherjee and Mulchrone 2013; Mulchrone and Mukherjee 2015, 2016; Mukherjee 2017) due to ductile/brittle deformation can have additional components.

In India, from the hydrocarbon point of view, the Jaisalmer and Bikaner–Nagaur Basin in Rajasthan are sedimentary basins occurring on the eastern flank of the proposed rift. However, the axis of the proposed transcontinental rift can be assumed to pass through present day offshore Kutch and Saurashtra (figure 13a) in an approximate N–S trend parallel to trend 4 of the Gondwana master basin in peninsular India (figure 1a). This passage of the rift-axis through offshore Kutch and Saurashtra implies maximum sedimentation in the area. Well 1 in offshore Saurashtra in proximity to the axis of the rift (figure 12) had produced oil from Lower Jurassic Sandstone (Mazumder *et al.*

2014) that is believed to be equivalent to Adrigat Sandstone (figure 12).

Additionally, hydrocarbon seepages could be identified in SAR images in the Kutch offshore and in Indus offshore area that could be classified to be of a high confidence level based on their repetitiveness indicative of proximity to a conduit to a mature petroleum system (figure 13a; Dave *et al.* 2013). These seepages in the Kutch and Indus offshore area are found to be aligned along the proposed rift axis associated with the presence of deep seated grabens containing pre-Trappean sediment (figure 13b, c). These grabens may be a part of the proposed Gondwana rift. In this context, it may be mentioned that the Karoo sourced oil and the tar balls shares many similarities with the hydrocarbon provinces of Indus basins (Roberts *et al.* 2011).

Figure 13. (a) Natural hydrocarbon seepages (encircled) of a high degree of confidence overlain on gravity data of Kutch and Saurashtra Offshore are found to be adjacent to the probable present day rift axis (black dotted line) and associated with deep seated Mesozoic grabens (figure 12c). (b and c) Show a longitudinal magneto-telluric profile (after Harinarayana 2008) along A1–A2 and a transverse seismic section along profile B1–B2 (after Dash *et al.* 2015) indicating the structural disposition of the Pre-Trappean rift sediments (Gondwanas?).

This indicates the apparent existence of rift related sedimentation with a well-developed and producible petroleum system in it. This might open up a new exploration frontier conceptualizing a Permo-Triassic basin in offshore Kutch and Saurashtra. This concept can be considered significant in the context that it is difficult to get a proper seismic image below the Deccan Traps in the area. Hence, such a concept based exploration might be helpful.

5. Conclusions

The above analysis puts forward a model of a Lower Gondwana rift extending from South Africa to Oman passing through Madagascar, Seychelles, Saurashtra, Jaisalmer, Bikaner–Nagaur of India and Indus Basin of Pakistan. Tectonically, this rift might be related to an aborted attempt of separation of Gondwana, with sedimentary records suggesting that it might have continued up to Early

Figure 13. (Continued.)

Jurassic. Since the axis of the proposed rift passes through offshore Kutch and Saurashtra, probability of the existence of a thick Late Carboniferous to Early Jurassic sediments may be there in these areas below the Deccan Trap. These pre-Trappean sediments may have an operative petroleum system similar to the producing fields in areas that were earlier connected by this rift. Considering this presumption, this concept might be instrumental in making offshore Kutch and Saurashtra area more prospective in terms of hydrocarbon exploration.

Similar GIS-based analysis may also be taken up for the tectono-sedimentary reconstruction of other hydrocarbon producing basins to redefine their prospectivity in space and time. One such exercise may be the tectonic reconstruction of the Ediacaran–Cambrian sediments in India in Bikaner–Nagaur and Ganga Basin trying to connect them with stratigraphically equivalent and hydrocarbon bearing sediments in Oman in the Arabian plate.

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