Geological evolution of Kachchh: an epitome of successive Phanerozoic events

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Kachchh geological province is conventionally referred to as 'Kachchh basin' or 'Kachchh rift basin' or even 'Kachchh aulacogen'. The geological records, however, recount a different history of the diverse depositional environment under diverse tectonic situations. The earliest Phanerozoic event was the deposition of Palaeozoic sediments during upper Permian and lower Triassic. Next event was a major marine incursion along rift zones coinciding with the Gondwana break-up and the initiation of northward drifting of the 'Indian land mass'. This was followed by the Reunion Plume related magmatism centring on the K–T boundary. Overlying this occur lignite deposits in the Naredi Formation correlatable with the global Eocene excursion. The Cenozoic basin closure corresponds to the major uplift in the Himalayas during the early Quaternary. Finally, the evidence of recurrent youngest block-movement-type active tectonics transformed the terrain into a zone of high seismicity.

Keywords: Cenozoic depositories, Kachchh, Palaeocene–Eocene thermal maximum, Phanerozoic events, Quaternary.

KACHCHH (also described as Kutch in the early literature) geological province, Gujarat, India is often referred to as 'Kachchh basin'[1–4], 'Kachchh rift basin'[5,6], or 'Kachchh aulacogen'[7], in tune with the usage by workers involved in the exploration of oil in the terrain. The expressions provide an impression of a single-stage evolution of Kachchh basin in a rift-related depositional condition for the entire post-Precambrian litho-units of diverse ages. Geological records, however, recount a different history involving several Phanerozoic events taking place under different tectonic and tectono-magmatic situations separated by periods of prolonged hiatuses.

Kachchh is truly a unique terrain in the Indian subcontinent not only because of the presence of active faults and related seismicity[8,9], but also for its Phanerozoic evolutionary history which bears records of global events responsible for the reconstitution of the Precambrian Indian Shield. The present study highlights this aspect of the geology of Kachchh, comparing the Kachchh Phanerozoic geological history with the contemporaneous global tectono-thermal events.

The Phanerozoic litho-formations of Kachchh, ranging in age from upper Permian to Holocene and consisting dominantly of sediments and some minor volcano-plutonic mafic ensembles are thought to have been deposited over an ensialic Precambrian basement. However, there is virtually no report on the occurrence of Precambrian rocks over the entire Kachchh 'basin' or to the west of it described as the Indus Fossil Rift zone in Pakistan[10], except on the occurrence of Malani volcanics and associated granites from the Kalinjur Hills of Nagar Parkar High[11] (now in Pakistan) and from the Maruda Hills in the Great Rann, about 25 km north of Khadir Island[12]. Although the extension of the Early Jurassic to Holocene sedimentary formations in the offshore part of the basin has been confirmed by drilling data, none of the offshore wells has been drilled deep enough to penetrate the older units representing the Precambrian basement[13].

The deposition of Jurassic formations along some basins in the Kachchh region, Gujarat, is traditionally known to be the oldest Phanerozoic ensembles in the region. More recent information based on bore-hole data indicated the presence of an older geological formation consisting of sandstone along with limestone and interbedded shale layers. This poorly known formation, occurring only in subcrops, has been described as 'unnamed unit' by Krishna[14], who has tentatively assigned an upper Triassic age for the ensemble. However, it would be rational to assign a Permo-Triassic age for the supposedly contemporaneous Kachchh Formation compared with the pre-Jurassic formations reported from Jaisalmer[15]. Such a correlation may appear justified in view of the known occurrences of stable shelf depositories of Permo-Trassic age at a number of isolated places around the Aravalli–Bundelkhand cratonic block of the Indian Shield.

The Kutch basin, as it is loosely described by different authors, is a unique depository of the Phanerozoic sedimentary formations of different ages forming a part of the western continental margin of the Indian subcontinent. The Kachchh basin bounded between the Nagar Parkar Fault (NPF) in the north and North Kathiawar Fault towards the south (Figure 1), continues in the westerly direction to merge with the basin situated at the southern edge of the Indus Shelf at right angles to the southern Indus fossil rift[10].

The Mesozoic basin of Kachchh is thought as a classic example of fault-controlled landform which developed only in this part of the western Indian subcontinent[12]. The succession of broadly E-W running 'arcuate' faults which segmented the Kachchh Jurassic basin is conventionally described as the reactivated Precambrian signatures, presuming that the NE-SW running Delhi–Aravalli orogenic trend has swerved towards the westerly direction after entering the Gujarat Plains[1,2,13,16]. Apart from Kachchh, the sub-parallel rift basin had also developed at Jaisalmer in

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western Rajasthan. In fact, the Mesozoic basins evolved only at these two places in the entire Indian subcontinent.

The reactivation theory in the evolution of Kachchh basins has been contradicted by Roy[17], who advocated that the formation of faults which bounded these basins evolved as newly developed fractures cross-cutting the pre-existing Precambrian trends. The suggestion gets strong support in the study of lineament pattern by Bakliwal and Ramsamy[18]. Based on the field relationship, the initial development of these basins has been correlated with the event of dismemberment (break-up) of the pristine Gondwanaland[17].

A Bajocian (~170 Ma) age has been generally accepted for the opening of these Mesozoic basins in Kachchh[13]. A recent study based on nanofossils in the marine transgressive sediments by Rai and Jain[19], however, indicated a Pliensbachian age for the earliest Jurassic ensemble in Kachchh. This age helps correlate the event of Jurassic basin opening in Kachchh with the first stage of Gondwana break-up conventionally assumed to have taken place about 180 Ma ago.

The final stage of deposition in the Mesozoic basins coincided with deposition of clastics in a prograding delta with the gradual regression of the sea[1], in response to the thermotectonic uparching of the western continental margin[13]. The faunal evidence from the youngest Mesozoic sediments indicated Santonian (~84 Ma) age for the inversion of the Mesozoic basins coinciding with the event of impingement of the Marion Plume under the Indian lithosphere[17]. Significantly, this was also the time of basin opening of Bagh–Lameta marine basins much inside the Indian land mass.

Following a hiatus of about 20 million years, a new volcano-plutonic magmatic event affected Kachchh between ca. 70 and ca. 64 Ma, i.e. entering on the K–T boundary. All these events happened during the impingement of Reunion Plume under the Indian continental lithosphere resulting in the formation of a series of extensional fractures which are now traceable on satellite imagery as faults or lineaments[8,18] (Figure 2). One such fracture is the NPF in the northernmost part of the Kachchh region, which preserved its pristine character in spite of the later geomorphotectonic events. Besides having arc-shaped geometry, NPF is characterized by the occurrence of water-filled radial furrows developing across the trace of the fault (Figure 3). According to Roy *et al.*[9], the feature developed along NPF is similar to the fjords seen along the western margin of Fennoscandian Shield, which are interpreted to have developed around a domal uplift[20,21].

The magmatism related to the impingement of Reunion Plume under the Indian lithoshphere occurred in two phases[17]. During the first phase several plutonic masses of alkali basalt composition intruded into the pre-existing sedimentary formations producing a series of ‘blister-like’ domes[22] (Figure 4) besides forming isolated plugs and irregular dyke-like intrusions. In certain instances the exposed domal outcrops show the intrusive plutonic body

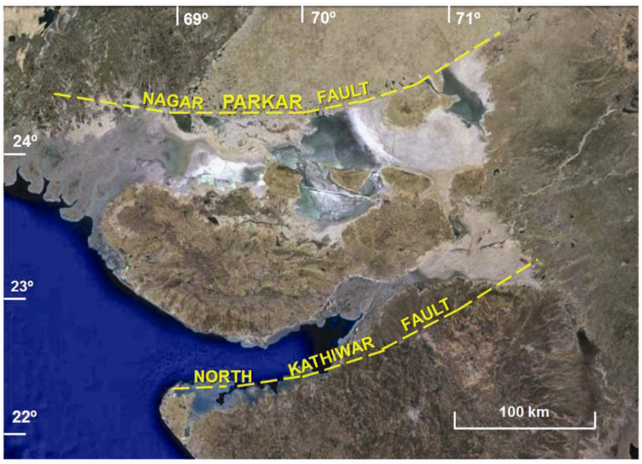

Figure 1. Geographic location of Kachchh basin, Gujarat, India between Nagar Parkar Fault (NPF) in the north and North Kathiwar Fault in the south, shown on Google satellite imagery.

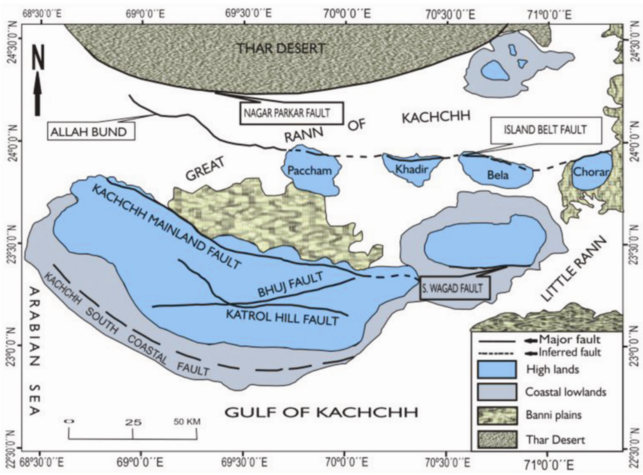

Figure 2. Geomorphotectonic map of the Kachchh region, showing disposition of the major faults in the area[8].

Figure 3. Satellite imagery showing water-filled radial furrows developing along the edge of the northernmost NPF[9].

in the core region (Figure 5). A coeval volcanic phase depositing alkali basalts is also reported by different authors[4,23]. The younger mafic volcanics include volcanic flows and ash beds with inter-trappean sediments overlying the eroded surfaces of Cretaceous beds[24].

Geochemical signatures of the magma bodies (both plutonic and volcanic rocks) suggest their origin because of the impingement of Reunion Plume under the Indian lithosphere[4,23]. The tholeiite basalt flows which include several inter-trappean beds of non-marine origin cover a wide region of west–central India. In the Kachchh region, the thoeiite basalt flows are noted only in the low-lying areas overlying the Upper Cretaceous formations.

Some isotopic information is available on Kachchh mafic magmatism. Pande *et al.*[25] reported $^{40}Ar/^{39}Ar$ 'plateau' ages of 67.3 ± 0.6 to 65 ± 1 Ma on plagioclase separates on mantle xenoliths-bearing alkali lavas. Venkatesh *et al.*[26] reported whole-rock plateau ages from 68.7 to 65 Ma for all flows except the uppermost tholeiite flow (F9). Correlation of alkaline magmatism of the Mundwara Complex in southwest Rajasthan with the Deccan magmatism at Kachchh is now favoured by recent workers. Considering this, the isotope ages reported by Basu *et al.*[27] from the Mundwara Igneous Complex assume significance. These authors obtained ca. 68.50 Ma age of primary biotite grains from the alkali olivine gabbro of the Toa pluton, Mundwara Igneous Complex. Similar age (69.36 ± 1.26 Ma) is reported for the hornblende grains from melagabbro of the region[27]. The weighted mean age of alkali pyroxenite of the nearby Sarnu-Dandali Alkaline Complex determined by Basu *et al.*[27] is 68.57 ± 0.08 Ma. Collating all these data, it is possible to compute an age range between ca. 69 and ca. 67 for the emplacement of alkaline basalt magma at different levels.

Figure 4. Satellite imagery showing closed outlines of a series of antiformal domes at Dudai near Bhuj, Gujarat[21].

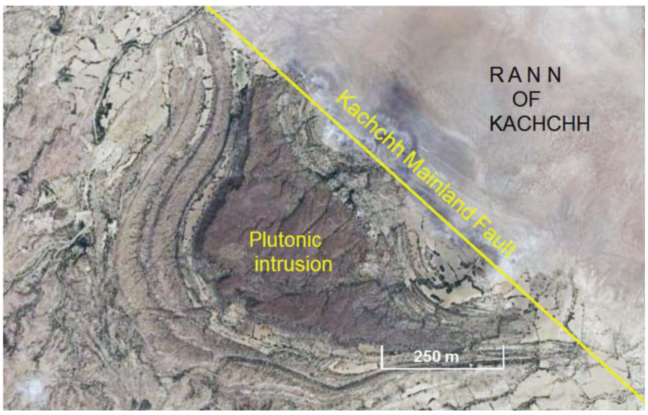

Figure 5. Plutonic intrusion of alkali basalt in the core of a truncated dome. (Inset) Outcrops of mafic rocks in the core region of the dome.

Field evidence provides a clear indication that the flows of tholeiite basalt which cover a wide region of west–central India, including Kachchh, formed later than the alkali basalts. However, because of lack of any definitive isotope age, it is hard to speculate the age of formation of tholeiite basalt flows. An inter-trappean bed containing anomalous, high Ir concentration is reported from Anjar area in Kachchh, which is considered as an evidence of bolide impact centring at the K/T boundary[28,29].

Courtillot *et al.*[30] proposed a two-phased model of Deccan volcanism based on isotope datings and palaeomagnetic data. The first phase of magmatism, according to these authors, took place within normal chron C30N, i.e. at 66.5/67 Ma. The second phase resumed with a short gap with the reverse C29R chron at ~65 Ma. However, using the isotope data described earlier from the alkaline complexes of Rajasthan, a little north of the Kachchh region, we may infer that the earlier phase could have taken place at ~68 ± 0.5 Ma between C31N and C30N chron. This indicates a time-span of 3–4 Ma between the two phases of Deccan magmatism.

Overlying the trap sequence occur Cenozoic formations along narrow strips fringing the Mesozoic outcrops. The coastal strips of the southern and western parts of Kachchh mainland expose the best developed Cenozoic succession in it. The major part of the Cenozoic formations occurs in the offshore region in the west extending up to the present level of the continental shelf[3]. In the region of the Great Rann, the Cenozoic rocks occur discontinuously along a narrow strip bordering the southern and western edges of Patcham Island (Figure 2). Continuous strips of Miocene rocks fringe the southern margins of Khadir and Bela Islands. In addition, narrow strips of Miocene rocks are exposed in the peripheral zones of Wagad Highland. A unique feature of the Kachchh area is a near-complete succession of sedimentary formations ranging from Palaeocene to Pliocene developed within the 900 m thick sequence[31]. The thickening of sedimentary deposits was primarily during the later half of the depositional history, i.e. approximately from mid-Miocene to Pliocene[31].

In general, the Kachchh Cenozoic basin represents a westward sloping platform with a progressive increase in sediment thickness from onshore to the shelf area and beyond. According to an estimate, more than 4.5 km of

Cenozoic sediments is present in the offshore belt[32]. These formations have a distinctive shelf facies character ranging in age between Palaeocene and Pliocene. The presence of continuously recognizable bands of key biostratigraphic horizons helped in building up a precise lithostratigraphic succession of the Cenozoic rocks of Kachchh[32].

The Cenozoic succession of Kachchh started with a basal, dominantly 'trap wash'-type deposit which is a product of residual weathering during a short hiatus subsequent to the flows of tholeiite basalt of Deccan Trap. These basal deposits constitute the Matanomadh Formation of Thanetian (Upper Palaeocene) age[33]. The Naredi Formation is the next higher succession which is well-known for the commercial deposits of lignite[32]. From a stratigraphic point of view, the lignite deposits form a part of the Eocene succession; but their precise age of development remains a debatable issue. Initially they were thought to be of the early Eocene period. More recent biostratigraphic studies on the samples collected from the lignite mines, however, indicated their age to be between late Lutetian and early Bartonian[32]. Temporally, the formation of lignite corresponds to the warming event of the Middle Eocene and suggests a humid climate at the onset of warming.

The Eocene period is reported to have witnessed hyperthermal events in the lower section[34] and in the Middle Eocene[35]. The prominent hyperthermal events include PETM (Palaeocene–Eocene Thermal Maximum), ETM2 (Eocene Thermal Maximum 2) and EECO (Early Eocene Climatic Optimum)[36,37]. A carbon isotope excursion has also been reported from the ETM 2 section[36]. According to Kozyem *et al.*[38], the negative excursion of carbon isotope is correlative with the global early Eocene excursion.

There is hardly any evidence to link the deposition of the post-Deccan Cenozoic formations with any rift-related basin. The entire phase of Cenozoic deposition took place along coastal shelves during a phase of tectonic quiescence (P. K. Saraswati, pers. commun.).

The top of the Cenozoic succession is marked by the Pleistocene and Recent miliolite along with the sand–silt-bearing Rann deposits[3]. A change in depositional condition is clearly marked in these deposits, suggesting the possibility that these are litho-stratigraphically different from the earlier Cenozoic formations. The Pleistocene and Recent together constitute the Quaternary Era, which is the time when the entire Indian subcontinent, including the Kachchh region underwent dramatic geomorphic changes. The Kachchh geological province provides unmistakable evidence of spectacular landform changes unknown in any other part of the subcontinent. The Great Rann of Kachchh, constituting the northern half of the terrain, is considered as a 'mysterious Quaternary terrain'[15], suggesting that the 'fascinating tectonic landscape' evolved only during a very short period beginning about 10,000 years ago. Even conceding that the landscape evolution started sometime earlier, say at around 50,000 or even 100,000 years ago, tectonically and seismically the region is known as the most active terrain in the Indian subcontinent[15]. The level of seismic susceptibility can be gauged by the fact that the region falls in Seismic Zone V, which by any standard is very unusual in a plate interior[9]. This is intriguing considering that the region is far away from active plate margin. Geophysicists describe the seismicity as 'stable continental region' earthquakes[39]. Studies also confirm that the topographic differences between the high and 'sunken' features are due to uplift and relative down-sagging during the geomorphotectonic evolution of the terrain[9]. The evidence constraining the time of geomorphological evolution of the terrain only during the late Quaternary proves it as the youngest neotectonically evolved terrain in the Precambrian Indian Shield.

The earliest recorded Phanerozoic event comes from the evidence of late Palaeozoic deposition ranging in age between upper Permian and lower Triassic sediments in a shelf sea that bordered the continental land mass of the Indian Shield. The geological entity encountered only in bore holes in the Kachchh region matches with similar patchy occurrences in western Rajasthan. The event can be correlated with the pre-Gondwana marine invasion of shallow sea in different parts bordering the Aravalli–Bundelkhand continental belt north of Narmada–Son Lineament.

The next event recorded in Kachchh was a major marine incursion along rift zones in tandem with a similar invasion of the sea in the Jaisalmer region in Rajasthan. Spanning between mid-Jurassic and mid-Cretaceous, or more precisely between Pliensbachian (~180 Ma) and Santonian (~84 Ma), the Mesozoic event can be correlated with the Gondwana break-up, and the consequent initiation of northward drifting of the 'Indian land mass'. The closure of this depositional event causing basin inversion, coincides with the outburst of the Marion Plume as the Indian Plate moved over it at about 90 million years ago. This was the time when Bagh–Lameta marine basins opened up much inside the Indian landmass.

Following a hiatus of about 20 million years, a new event affected Kachchh which lasted for a short time period between ca. 69 and 65 Ma, i.e. centring on the K–T boundary. The magmatism is manifested in the form of an early plutonic and later volcanic mafic magmatism. The plutonic masses of alkali basalt composition intruded into the pre-existing sedimentary formations producing a series of blister-like domes, besides forming isolated plugs and irregular dyke-like intrusions. The younger phase of mafic magmatism is manifested as mafic volcanic flows (Deccan Trap) with intervening inter-trap beds and in certain cases by ash beds. A number of narrow dykes occur mainly to the north of the lava-flow occurrence. Geochemical signatures of the magma bodies (both plutonic and volcanic rocks) suggest their origin to the interaction of the Reunion Plume outburst and the Indian lithosphere. Another significant manifestation of the plume outburst in the region is the development of a series of parallel fractures which are traceable on satellite imagery as lineaments. The development of radial cracks, now filled with water, in the former testifies its evolution due to large scale crustal doming during the (Reunion) plume outburst. Overlying the trap sequence occur the Cenozoic formations, which developed mainly in the coastal belt in western and southern Kachchh. The timing of basin opening marks the Asia–India collision event. Showing a distinct shelf facies character, the Cenozoic sedimentary formations range in age between Eocene and Pliocene.

The most significant feature in Cenozoic stratigraphy is the occurrence of lignite deposits in the Naredi Formation of Eocene age. The Eocene period has also witnessed a number of hyperthermal events described as PETM, ETM 2 and EECO[35]. A carbon isotope excursion has also been reported from the ETM 2 section[36]. The negative excursion of carbon isotope can be correlated with the global Early Eocene excursion[37].

PETM has become a focal point of considerable geoscience research because it probably provides the best past analogue to understand the impacts of global warming and massive carbon input to the ocean and atmosphere, including ocean acidification.

The Cenozoic basin closure coincides in time with the major uplift event of the Himalaya during the early Quaternary. Apart from deposition of miliolite and sand–silt-bearing Rann deposits, the youngest block-movement-type active tectonics made the terrain a zone of high seismicity comparable to that of plate boundaries.

Summarizing, the Phanerozoic geological history of Kachchh is marked by repeated changes in depositional conditions taking place under diverse tectonic environment. It would be, therefore, improper to refer to the Kachchh Phanerozoic depositories simply as 'Kachchh basin' or 'Kachchh rift basin' or 'Kachchh aulacogen'. The multiphase depositional history of Kachchh matches with the global events that shaped the Precambrian Indian Shield during the Phanerozoic.

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