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A Case for Revisiting the Evolutionary History of Pericratonic Cambay Basin, India.

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Summary

The petroliferous NNW-SSE trending elongate and arcuate Cambay Basin predominantly contains Quaternary and Tertiary sediments over Late Cretaceous Deccan Trap. In the northern part, however, drilled wells indicate that this sediment package directly overlies Mesozoics above Precambrian basement. The basin has been perceived as a failed rift arm of a four-way mega fracture system formed near the present-day west coast of India. This fracture system is considered to have originated due to the impingement of Reunion Mantle Plume during the Late Cretaceous on Indian lithosphere, which was moving northwards subsequent to the breakup of Gondwanaland.

A number of geological and geophysical observations and certain recently published developments indicate that many issues pertaining to the evolution of the basin require a relook. Indications are that Cambay Basin may not be a typical rift and the presently accepted history of evolution of the basin needs to be revised. The recent developments in the understanding of plate motion reconstructions off the western continental margin of India accentuate this necessity. This paper presents some of these developments and incongruities in the perceived evolutionary history of the basin, and makes a case for revisiting these issues. Such an exercise will also provide new perspectives for further exploration thrusts in what is generally perceived to be a maturely explored basin.

1. Introduction

Cambay Basin is a roughly NNW-SSE trending petroliferous graben situated in the northwestern margin of Indian peninsula in the state of Gujarat (Fig. 1). It is variously described as an intracratonic type basin (Mathur et al., 1968), an avlacogen (Raju, 1968) and a pericratonic rift basin (Biswas, 1987). Mathur et al. (1968) identified it to extend from Banas River, north of Mehsana Town in Gujarat, through the alluvial plains of Gujarat, to the Gulf of Cambay near Surat and further southwards into the Arabian Sea. They perceived the basin as a narrow arcuate graben with a gentle turn to west in the northern part. Tharad and Sanchor depressions were later included as part of the basin, thus giving an eastward swing to the basin at its northern extreme (Dhar & Bhattacharya, 1993). Sustained campaigns of geological and geophysical surveys led to the first hydrocarbon discovery in 1958 (Dhar & Bhattacharya, 1993). The basin has since then witnessed ever-increasing exploration efforts, leading to an

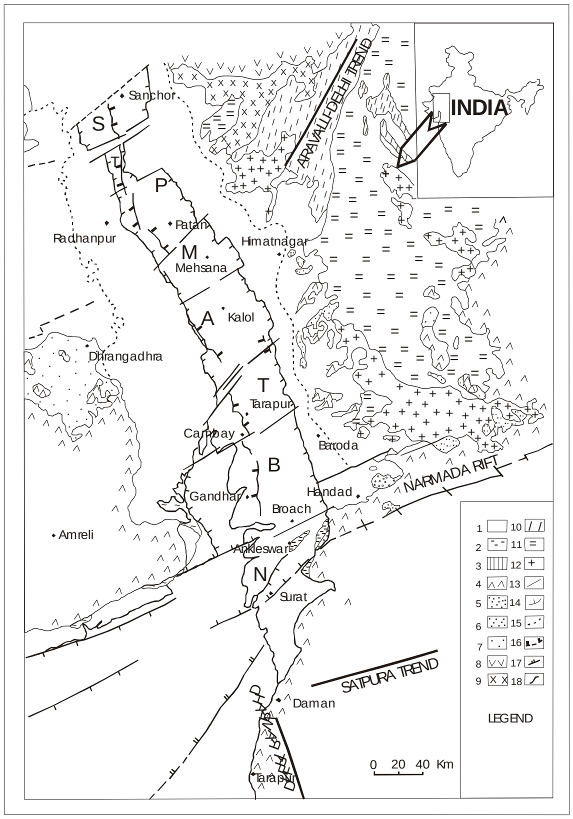

Fig.1. Geological map of Cambay Basin (Legend and Source: Kundu and Wani, 1992)

impressive coverage of virtually the entire basin by geological, geophysical and drilling campaigns.

Due to the difficulty in penetrating through drilling and by geophysical methods, the Deccan Trap is taken as the technical basement over major part of the basin, save for the northern part where drilled wells have encountered Precambrian basement underneath Quaternary, Tertiary and Mesozoic sediments (Singh, 2000).

The basin is extensively covered by geophysical data and has witnessed intensive drilling campaigns. However, the density of wells varies over the basin, with concentrations over known and producing fields. Most of the wells terminate within Miocene and Eocene, which are the major producers. The wells that have reached Trap are mostly located near the margins. Only a handful of wells had penetrated Deccan Trap and reached basement. The scarcity of wells reaching/penetrating Trap and inherent limitations in the penetration of seismic data to the deeper parts of the basin makes the understanding of the basin, particularly the deeper central part, somewhat incomplete and offers plenty of scope for study and further exploration efforts. Cambay Basin derives its importance by virtue of its established hydrocarbon potential and scope for future discoveries. A better understanding of the subsurface geology of the block would contribute to a better understanding of ips petroleum systems and prospectivity. Iany workers linked the evolution of Cambay Barin to phat of western continental margin of India. An analysis of the evolutionary history of the basin could give vital leads about this link.

2. Genesis of the Basin

Mathur et al. (1968) described Cambay Basin as an intracratonic type basin that was carved out by reactivation along older fault trends in Cretaceous. They indicated that the formation of the westerl ckast of India and the origin of the Cambay Basin are related. According to Biswas (1982), the basin opened up in Early Cretaceous time during India’s northward drift after breakup from Gondwanaland in the Late Triassic – Early Jurassic. The presently popular perception on the evolution of the basin is that it is a failed rift arm (Burke & Dewey, 1973; Biswas, 1982, 1987). According to this model, subsequent to the breakup of Gondwanaland in Late Jurassic, India was attached to Madagascar and Seychelles till about 90 Ma. Then, India and Seychelles separated together from Madagascar around 90 Ma and moved in NNE direction. During this movement, they encountered a nearly stationary mantle plume at the location of what is presently the Reunion Island. The plume, which was ascending to the surface during this episode, impinged the Indian lithosphere somewhere near what is presently Surat towards the end of Cretaceous. The hot plume material uplifted the area around the location of impingement and as a result, a four-way radially deviating mega-fracture pattern developed. The nearly N-S trending two fractures yielded further to extensional stresses, ultimately resulting in the breakup between Seychelles and India along these fracture arms. The eastern part of these extending fractures formed the present-day continental margin of India. Narmada Geofracture zone formed the third arm while the fourth arm gave rise to Cambay Basin under extensional stresses associated with the separation and movement of India away from Seychelles. Rifting in Cambay Basin is considered to be coeval with the breakup of India and Seychelles and the emplacement of Deccan Basalts in Late Cretaceous. The rifting process continued through the Paleocene period, followed by the on-going post-rift subsidence phase, which resulted in accumulation of Tertiary and Quaternary sediments. The direction of dominant extensional stress direction has been identified to be ENE-WSW and is considered to have rotated over time (Kundu and Wani, 1992). However, the basin exhibits certain prominent features that indicate that it may be very different from a typical rift.

3. Distinctive Features of the Basin

3.1 Geometry of the Basin:

One of the most striking features of the basin is its broadly smooth arcuate outline, which is also discernible on Bouguer anomaly map (Fig.2). Perhaps no other

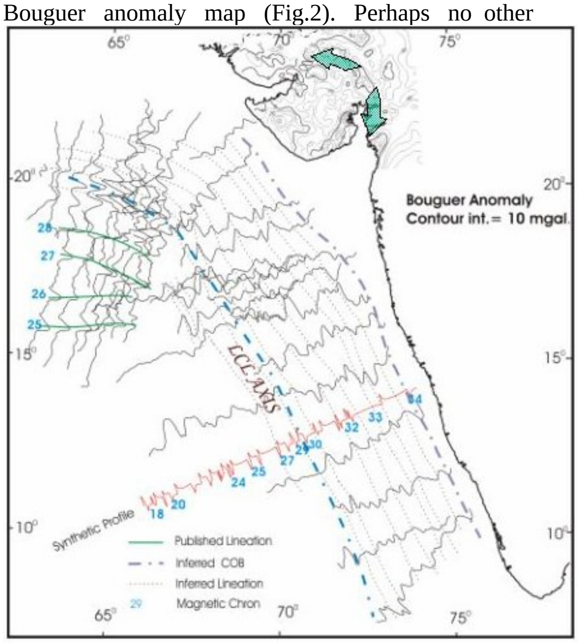

Fig. 2. Composite map depicting magnetic anomaly lineations in Eastern Arabian Sea and Bouguer anomaly of Cambay Basin and adjacent region (Source: Rangarajan (2006) and Raval (2001)).

published rift basin exhibits such a character. Most of them like the East African rift system, Rhine graben, etc have zigzag outline. Morley (1995) and Freund and Merzer (1976) assert that zigzag outline is characteristic of rifts. On comparable lengths, while these rift basins exhibit disjointed dogleg shaped segments, Cambay basin has continuous and nearly concentric margins, save for the slight broadening towards the southernmost part, south of Narmada River. Over the Bouguer anomaly map, the nearly circular outline of the basin appears to continue westward into Kutch-Rajasthan area and its western/northern end is not clear (Fig. 2). Crustal velocity structure inferred from earthquake data also indicates its western extension (Kennett and Widiyantoro, 1999). Mathur et al. (1968) originally identified it to extend from slightly north of Mehsana up to Gulf of Cambay, as a narrow arcuate basin, concave to the west. Later, Tharad and Sanchor depressions were included as part of the basin, thus giving an eastward swing to the basin at its northern extreme (Dhar & Bhattacharya, 1993). However, the Bouguer anomaly map doesn't indicate these blocks to follow the logical extension of the trend observed in the rest of the basin south of these blocks.

It may be noticed that there is a rough sub-parallelism between the outline of the basin and the bathymetry off the west coast. Also striking is the colinearity between the trend of the basin and the trend of free-air anomalies and magnetic anomaly lineations off the west coast (Fig. 2; Rangarajan, 2006). These aspects have hardly been addressed. In the context of the theory of seafloor spreading, the magnetic anomaly lineations are considered to trend orthogonal to the direction of drift motion of the adjacent continental block. In view of this, the perceived relationship between the evolution of Cambay Basin and that of the adjacent Eastern Arabian Sea needs to be reviewed.

3.2 The effect of Primordial Trends:

Biswas (1982, 1987) observed that Cambay Basin is crossed by a number of primordial trends. From north to south they are the NNE-SSW trending Delhi trend, NE-SW trending Aravalli trend and nearly E-W trending Satpura (Narmada) trend. Daly et al. (1989) have observed that in typical rifts like East Africa rift system, the primordial trends play an important in defining the trend and architecture of the basins. These rifts appear to have their strike offset along these trends and skirt the cratonic blocks associated with these trends (Fig. 3). However in the case of Cambay Basin, as can be seen from Bouguer anomaly map (Fig. 2) and geology (Fig. 1), the primordial trends do not have any effect on the nearly circular trend of the basin. At best, they define the boundaries of the tectonic blocks into which the basin has been divided.

3.2 The Crossing Rifts:

Another intriguing observation is that Cambay Basin and Narmada Basin cross each other at nearly orthogonal angles (Fig. 1). This is perhaps the only case wherein the two grabens criss-cross each other with apparently no effect on each other. In all other published examples known to

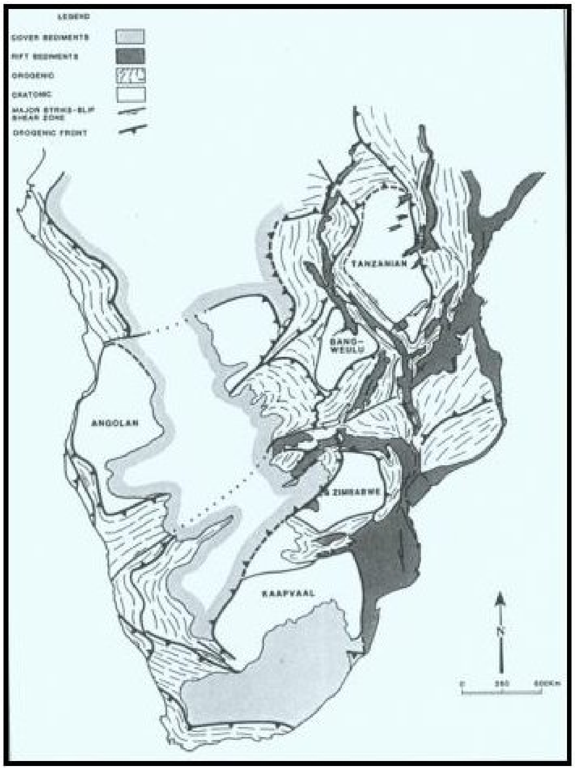

Fig.3. Primordial trends and mobile belts in eastern and southern part of Africa and their relation to the Eastern African and Karroo rifts (Source: Daly et al., 1989).

the author, when two or more rifts with oblique trends come together, one of the rifts continues its trend and the rest terminate against it (e.g., Guiraud and Maurin, 1992; Guiraud and Bosworth, 1997). Such a feature may be observed to the east of Cambay Basin also with respect to Narmada Basin on one hand and Pranahita Godavari, Mahanadi and Damodar basins on the other. These basins terminate against Narmada Graben without indications of northward continuation across it.

3.3 Extensional Stresses:

An additional issue regarding the absence of influence of the primordial trends on the evolution of Cambay Basin is that of the direction of inferred extensional stresses. It may be seen that the NE-SW extensional stress direction that is inferred to have provided the initial stress during the rift stage of evolution of the basin (Kundu and Wani, 1992) is sub-parallel to the Delhi and Aravalli trends. Under such extensional stresses, these primordial belts would have provided pre-existing zones/planes of weakness to expend the stresses. This would have resulted in preferential reactivation of these surfaces and clearly discernible offsets in the axis/strike of the basin at the location of crossing of the two trends, similar to the inference derived in East African rift system, Rhine graben etc. However, as pointed out earlier, the basin does not display any such offsets in its smooth circular margins.

If the basin extended under the influence of extensional stresses, then the crust adjacent to the linear margins of the basin should bear evidence of such a motion. It is logical to expect that the crust adjacent to the basin would have been subjected to compressional stresses from the extending margins of the basin, leading to conspicuous folds parallel to the margins. No such features are noticeable and the trend of the older rocks adjacent to the margins is essentially NNE-SSW to ENE-WSW (Fig. 1). As noted by Choudhary (1975), characteristic triangular rift shoulders expected in a typical rift are also conspicuously absent in Cambay Basin.

4. Disparities in the Concept of Evolution of the Basin

4.1 Plume Related Uplift:

The presently accepted popular theory of genesis and evolution of the basin also faces a number of hurdles. The Reunion mantle plume is considered to have played a prominent role in the genesis of the basin. However, the concept of mantle plumes itself faces many problems, with evidences contrary to the concept mounting continuously (a good compilation of such issues is available at www.mantleplumes.org). The existence of Reunion plume has been severely questioned (Sheth, 1999, 2005). The occurrence of pre-rift uplift also has been disproved in most of the cases (Ziegler, 1992). According to Ziegler (1992), virtually all the well-studied rifts indicate an episode of pre-rift subsidence. Thus, the uplift related four-way fracture proposed in the case of Cambay Basin appears to be a doubtable concept. The nature of the mega-fracture system also is a matter of concern. Worldwide examples of triple junctions invariably involve linear rifts. The smooth arcuate geometry of the Cambay rift makes it an unlikely candidate of fracture formed out of crustal uplift.

The model involving lithospheric uplift and fracture formation has yet another problem to surmount at the conceptual level. According to Burke & Dewey (1973), for a mantle plume to cause uplift and fractures to form, the location of impingement at lithosphere has to be steady over the plume for a reasonable amount of time to take effect. However, as per plate tectonic models, India was in motion from Late Jurassic onwards if not earlier. This motion appears to have been accentuated after inferred separation of India from Madagascar when the impingement of Reunion Plume on Indian lithosphere is supposed to have occurred (e.g., Schlich, 1982). This observation adds another element of doubt about the perceived uplift and formation of radial mega-fractures.

4.2 Association with Plate Separation:

The association of initiation of rift in Cambay Basin with the breakup of India and Seychelles needs to be revised. A number of authors indicated the existence of pre-Tertiary phase of seafloor spreading just to the west of the present day shelf edge off the western continental margin of India (e.g., Masson, 1984; Bhattacharya et al., 1994; Malod et al., 1997). Rangarajan (2006) brought out a number of observations, which require that, the Continental Oceanic crustal boundary off the western continental margin be near the present day shelf edge. When viewed in the context of presently available plate reconstruction models, it leads to the logical inference that Seychelles had broken away from India along with Madagascar around 90 Ma itself. That is, by the time rift phase in Cambay basin is inferred to have initiated in Late Cretaceous – Early Paleocene, seafloor spreading was already in motion off the western continental margin of India for about 30 Myr.

4.3 Association with Deccan Basadt Outpouring:

The inferred association of emplaaement of Deccan basalts with initiation of rifting in Cambay Basin also needs a relook in view of the problems associated with the various elements of the presently popular model for evolution of the basin. It has been pointed out earlier that some of the wells drilled in the northern part of the basin did not encounter Deccan Trap before reaching the basement. This indicates the probability that Deccan Trap is restricted to the area south of these wells. Various studies have indicated that Deccan Traps have been emplaced as flood basalt flows. Flood basalts are known to travel large distances, often of the order of 4000km as in the case of Columbia Flood basalts. The area near the junction of Narmada Basin and Cambay Basin near Surat is considered to be a prominent center for the outpouring of Deccan basalts (Bhattacharji et al., 1996). Recent studies have indicated that the Deccan flood basalts from such places of origin had traveled along the pre existing Narmada Basin and then on to the Pranahita-Godavari Basin to reach as far as Rajahmundry near the east coast of India (Baksi, 1994, Knight et al., 2003). It is then possible that the Deccan flood basalts have also traveled along Cambay Basin if it were pre-existing and reached up to the area south of the wells that have not encountered trap. The presence of Mesozoics in the wells of the basin that have either penetrated Trap or reached basement indicates the possibility of existence of a basin in the pre-Tertiary period. Biswas (1982, 1987) also indicated that the basin formed in Early Cretaceous itself. The pre-existing topographic gradients in the basin and the velocity of movement of the flood front might have been such that the flood basalts could travel up to this distance northwards from the location of their outpouring. Additional indications that the basin predates the Deccan basalt flows comes from the fact that in some of the wells near the central part of the basin like North Kadi-1 and Linch-3, Tertiary sediments overlie hornblende syenite and basalt is absent (Ramanathan, 1981).

5. Implications

The implications of the disparities pointed out in the preceding sections are manifold. The possibility that Cambay Basin existed prior to the outpouring of Deccan basalts brings in new perspectives. For example, the perceived causative relationship between rifting and basalt emplacement in the basin needs a relook. In addition, the role of the basalts in the evolution of the basin and sedimentation in the basin needs to be studied. Being of high density, they might have contributed dominantly to the subsidence in the basin from rift stage onwards. That is, there is a distinct possibility that the vertical movements during the rift stage of the evolution of the basin has been overlooked or underestimated in comparison to the horizontal movements inferred from perceived extensional stresses in operation during this stage. This aspect gains additional significance in the context of absence of evidences of horizontal movements in the basin brought earlier like (i) the anticipated linear folds adjacent to the basin paralleling the trend of the basin and (ii) the linear shoulders anticipated in a typical rift. The geothermal and pressure conditions that are entailed by the Deccan basalts on the preexisting Mesozoic sediments have a bearing on the prospectivity of the Mesozoics, which has of late been of interest.

At one level is the necessity for revision of various elements in the conceptual framework of the origin and evolution of the basin. The existing ideas on the evolution of the basin are based on the concepts of plate tectonics and seafloor spreading. Revisiting this conceptual framework is necessitated by the recent developments and additional information generated in these fields. Since the evolution of Eastern Arabian Sea and that of the basin has been linked by various authors, the recent developments in the understanding of the evolution of the western continental margin of India have a bearing on the evolution of Cambay Basin and as such needs to be revisited. Some of the concepts that have been invoked by the earlier authors in the evolution of the basin like mantle plumes and continental drift have been severely challenged of late. These issues also provide additional necessities for a relook at the presently popular models of evolution of the basin.

The presently accepted conceptual framework of evolution of Cambay Basin involves extensional stresses and as such envisages predominant role for horizontal movements in the evolution of the basin. The current approach to prospectivity is based on these perceived horizontal stresses and associated structural and stratigraphic environment. As brought out in the previous sections, the role of vertical movements in the basin has been largely ignored. The shift of focus to vertical movements would logically entail a shift from the current approach with a resultant new framework involving associated structural and stratigraphic elements. These will essentially lead to new approaches to prospectivity in the basin. This gains prominence in the ever-increasing search for hydrocarbons in the basin. Till recently the major part of exploration efforts in the basin veered around Eocene and Miocene prospects and of late efforts have progressed towards deeper prospects. A shift in the approach will add new perspectives and new plays. As such, the revisiting of the existing concepts as has been advocated in the present paper will be worth its effort.

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