



# Structural analysis and seismic stratigraphy for delineation of Neoproterozoic-Cambrian petroleum system in central and eastern part of Bikaner–Nagaur basin, India

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## Abstract

Bikaner–Nagaur basin is located in the northwestern part of India and lies on the rising flank of Punjab platform of Middle Indus basin in Pakistan. Existence of Neoproterozoic-Cambrian petroleum system was confirmed by the exploration activities in the western periphery of the basin, whereas vast areas of central and eastern parts remain unexplored. Knowledge of petroleum system in this unexplored part of the basin is limited due to non-availability of data. Recently, 2525 line km of regional 2D seismic data acquired for the first time by Government of India under National Seismic Program (NSP) unlocks the opportunity for comprehensive understanding of subsurface geology in unexplored part of the basin. Present work aims to interpret recently acquired 2D seismic data and integrate with available surface (outcrop) data, gravity and well data (drilled in western part of basin) for unfolding the petroleum system elements, structural configurations and stratigraphic features in the hitherto central-eastern part of the basin. Two Neoproterozoic-Cambrian hydrocarbon plays: (1) Jodhpur and (2) overlying Bilara/Hanseran Evaporite Group (HEG) were envisaged. Both the plays depicted distinctive seismic characteristics, structural alignment and distribution of reservoir, source and seal. Fluvio-deltaic sandstone within Jodhpur group and shallow marine fractured dolomites within Bilara/HEG showed potential reservoir characteristics whereas organic rich laminated dolomites, stromatolites and argillaceous litho-units within Bilara/HEG group have been predicted as prospective source. The Halite layers within HEG group were considered as effective regional seals. Fault bounded anticlinal structures associated with Cambrian compression have been identified as the main entrapment for hydrocarbon accumulation. The basin witnessed long tectonostratigraphic history with two major compressional phases. Structures formed by Cambrian compression are likely to be charged as the time of source maturity and peak expulsion was later, during early Mesozoic period. Overall, the study indicates new opportunities and potential accumulation of hydrocarbon in the unexplored part of the basin.

**Keywords** Bikaner–Nagaur basin · Seismic · Structural configurations · Hydrocarbon plays · Leads

## Introduction

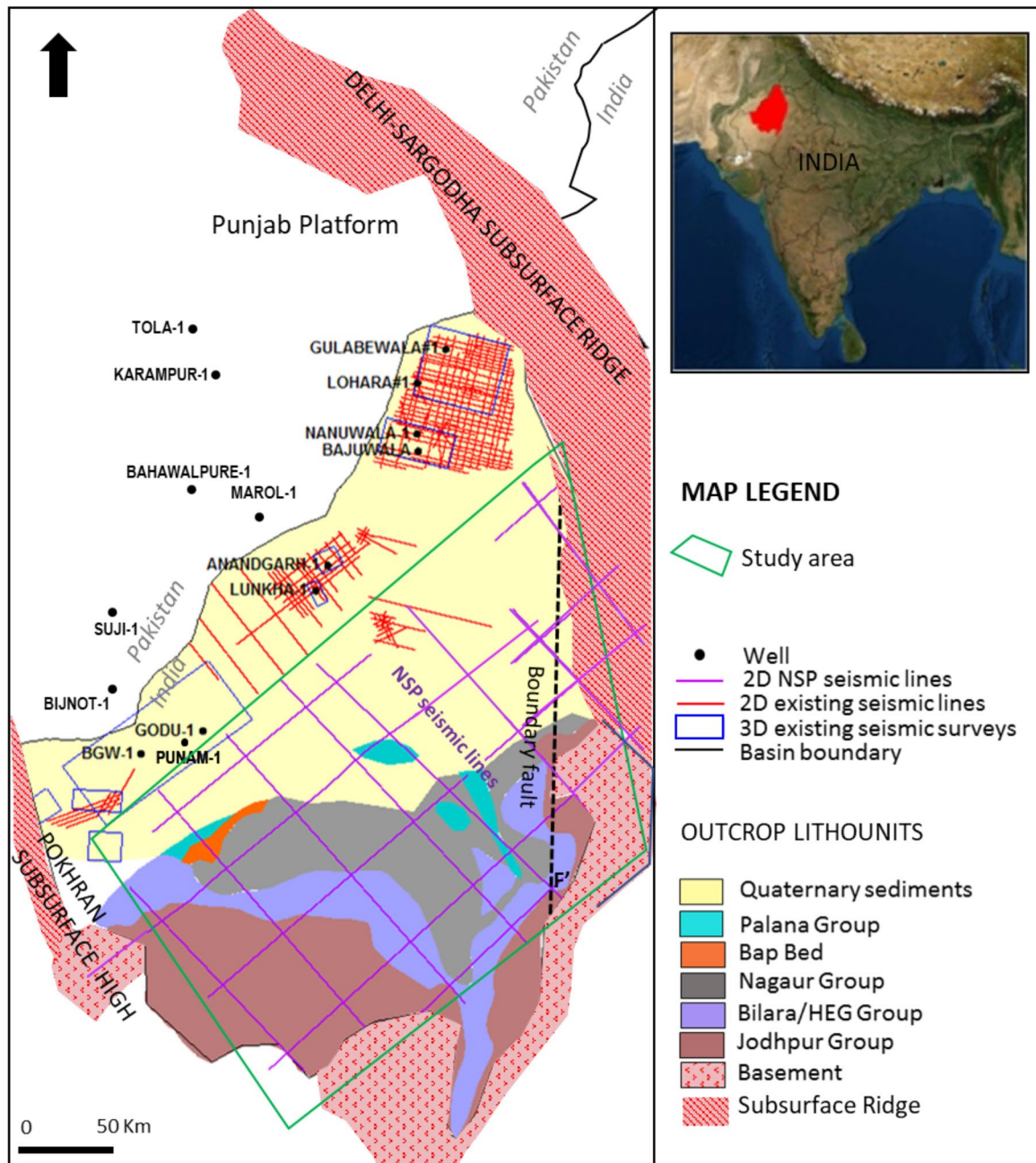
Bikaner–Nagaur basin, a pericratonic basin (Ram 2015), occupies an area of ~77,500 sq. km and is located in the northwestern part of the Indian shield. The basin is filled by Upper Proterozoic-Lower Palaeozoic sediments of Marwar Supergroup with maximum thickness of 1500 m (Kumar and Chandra 2005) and is overlaid by thin cover of Mesozoic and Tertiary sediments. The basin is bound by Delhi Sargodha basement high in the north and north-east, Aravalli fold belt

in the east and Pokhran high in the south west as shown on Fig. 1. It further extends toward the west to Punjab platform of Middle Indus basin in Pakistan.

Until now, exploration activities have been confined to the western periphery of the basin where hydrocarbon potential of Proterozoic Jodhpur and Cambrian Bilara formation is already established. However, large areas of central-eastern parts, nearly 60% area of the basin, were virtually unexplored. Lack of subsurface data, limited knowledge on the geological processes and unknown elements of petroleum system were major constraint to expand the exploration activity in the region. Even if the proven petroleum system exists within the unexplored area, presence and continuation of petroleum system elements are yet to be ascertained. Regional 2D seismic acquisition (in 2018) under the

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**Fig. 1** Location of Bikaner–Nagaur basin with respect to adjoining basins. Map depicts availability of surface data (outcrop) and subsurface data, wells and seismic data in Bikaner–Nagaur Basin; NSP 2D lines marked by purple color; study area marked by green color

National Seismic Program (NSP) funded by Government of India expanded the scope of assessing stratigraphic, depositional and structural configuration in the area.

Under the present study, newly acquired 2D seismic data of central and eastern Bikaner–Nagaur basin have been interpreted incorporating available well and seismic data of western part of the basin to describe geology, structure and hydrocarbon potential of the study area (Fig. 1).

This study aims to gain a reasonable understanding on the presence and distribution of the elements of petroleum system, structural configurations and stratigraphic features in central and eastern region of the basin by taking inference from explored area of Bikaner–Nagaur basin. This would aid in future exploration activities in this vast region.

## Geological settings

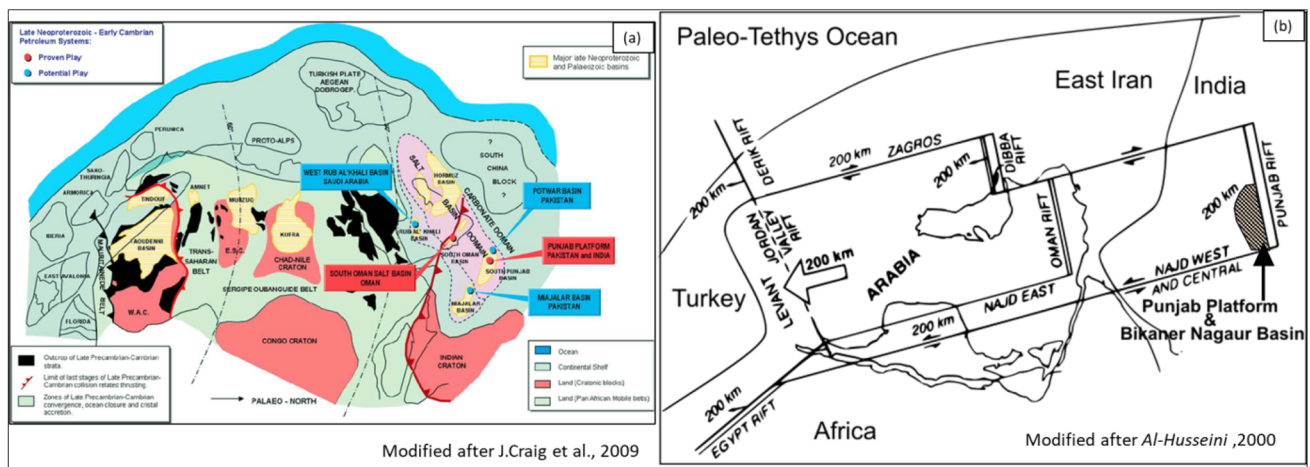
Paleogeographic reconstructions suggest that Bikaner–Nagaur basin was formed by extension along Najd fault system of Arabian plate during late Proterozoic–early Cambrian period, related to the latest phase of Pan-African orogeny (Pollastro et al. 1999; Al-Husseini 2000; Dmitry et al. 2007) (Fig. 2b). NW–SE trending ~1000 km of the Najd fault system exposed Arabian shield and was active between Late Neoproterozoic and early Cambrian (Luning et al. 2009). Sinistral movement along Najd faults formed a series of rift-grabens including Punjab rift and Bikaner–Nagaur basin in the eastern part of Gondwanaland (Fig. 2b) during late Neoproterozoic time (Al-Husseini 2000). Pericratonic Bikaner–Nagaur basin holds sedimentary succession primarily from Neoproterozoic to early Cambrian in age, namely Marwar supergroup, that consists of (i) Jodhpur group (ii) Bilara and Hanseran Evaporite Group (HEG), and (iii) Nagaur group in the chronological order and overlaid by thin cover of Mesozoic and Tertiary sediments (Fig. 3) (Prasad et al. 2010).

Jodhpur group is a syn-rift fluvio-deltaic deposit, followed by a transgressive carbonate-halite Bilara-HEG group. Mazumdar and Strauss (2006) confirmed the age equivalence of Bilara carbonate and HEG halite based on the sulphur and strontium isotopic analysis (Mazumdar and Strauss, 2006). The gradational contact with overlying Nagaur Group marks the onset of clastic deposition with thick shale and sandstone representing fluvial and lacustrine deposition. Marwar Supergroup of Bikaner–Nagaur basin (India) is regionally correlated with Salt Range Formation of Pakistan; however, Marwar

Supergroup (in India) is relatively thin and less deformed (Cozzi et al. 2012; Chauhan et al. 1991, 2004).

## Exploration history

During 1950s, gravity-magnetic surveys were carried out by Oil and Natural Gas Corporation (ONGC) to decipher the configuration of the Bikaner–Nagaur basin. This data revealed that Pokhran-Nachna high, a prominent gravity high, separated Jaisalmer & Barmer basins from Bikaner–Nagaur basin. In early 1960s, the first parametric well Pugal-1 was drilled by ONGC and encountered ~1 km thick sedimentary succession ranging from Cambrian to Tertiary in age. In 1991, Oil India Limited (OIL) drilled the first discovery well, Baghewala-1 in the western periphery of the basin, which confirmed the presence of heavy oil (17.6° API) within Jodhpur sandstone and bitumen in Upper and Lower Bilara carbonates (Oil India Limited 1991). Since then wells drilled along the western periphery of the basin confirmed presence of two Neoproterozoic-Cambrian plays e.g., Jodhpur play and Bilara/HEG play. Geochemical similarity in oil samples obtained from Well Baghewala-1 (in Bikaner–Nagaur basin), and Well Karampur-1 (in Punjab platform) with the oil specimen from the Carbonate-Evaporite source rock of Huqf Group (South Oman) provided strong evidence for correlating Bikaner–Nagaur basin to Punjab platform and prolific South Oman basin (Peters et al. 1995; Sheikh et al. 2003). Cozzi et al. (2012) highlighted the similarity in litho-, chemo-stratigraphy, evolution of facies and elements of hydrocarbon play among Huqf supergroup of Oman with the time equivalent counterparts of Marwar supergroup in Bikaner–Nagaur basin and Salt Range formation of Pakistan. Previous oil and gas exploration activities



**Fig. 2** a Paleogeography of the ‘Peri-Gondwanan Margin’ (c. 610–520 Ma) during late Neoproterozoic–Early Cambrian (Craig et al. 2009), b Sinistral dislocation of 200 km along Najd Central and West

faults results opening of Punjab Rift- Bikaner–Nagaur basin during late Neoproterozoic time (Al-Husseini 2000)

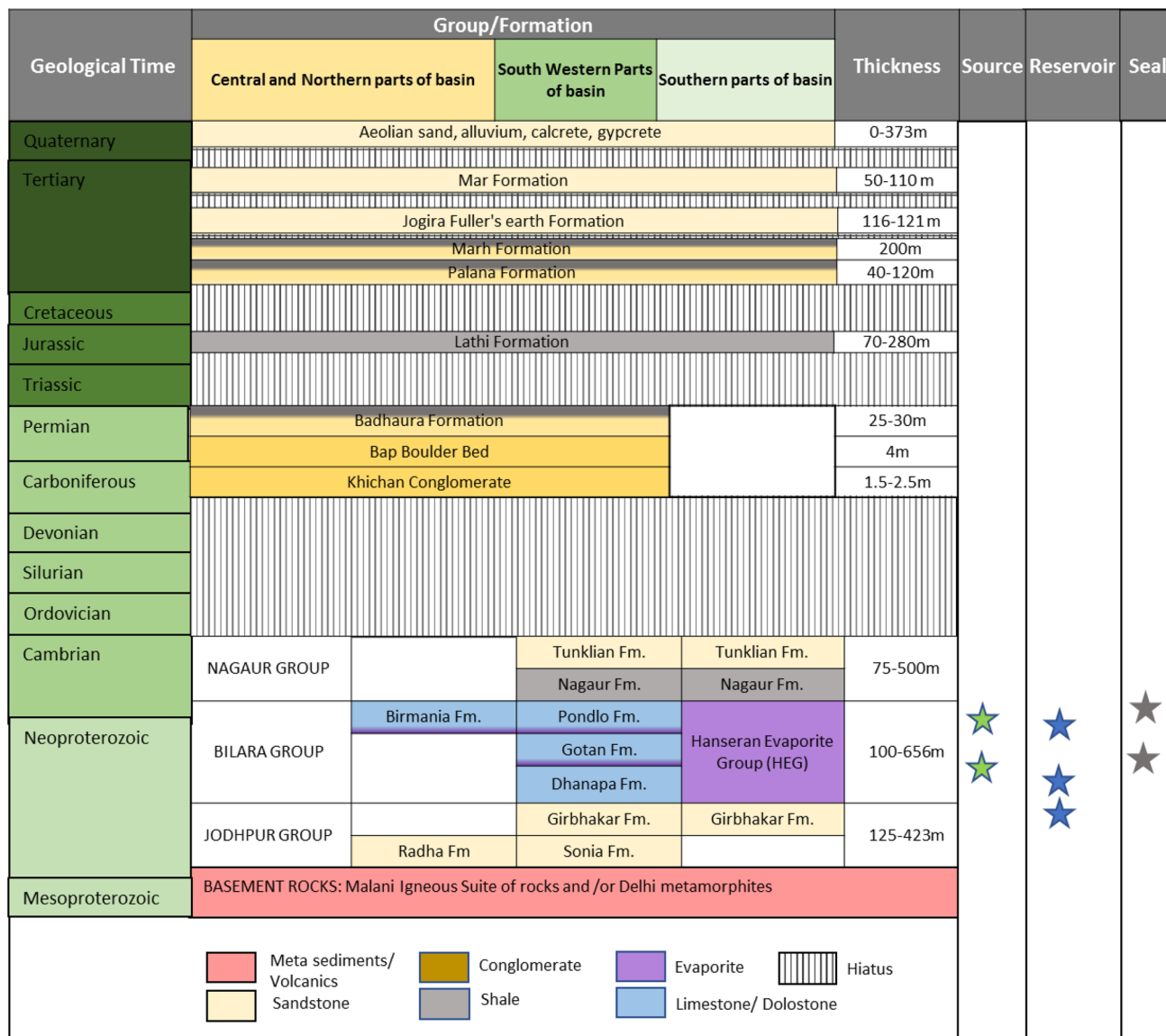


Fig. 3 Stratigraphy (Redrawn after Kumar et al. 2005) along with tectonic event summary of Bikaner–Nagaur subsbasin

were primarily focused in and around western margin of the basin. Vast central and eastern parts of the basin remained unexplored until now.

**Data availability**

The study is based on 16 profiles of 2D regional seismic reflection data acquired under NSP of total 2525 Line Kilometer (LKM) along with selective sections of 2D seismic (3294 km) and 3D seismic (2348 sq. km of the surveys RJ-ONN-2004/1-3D north-central, RJ-ONN-2004/1-3D south, RJ-ONN-2004/2, Bhagewala-area-3-ML and

RJ-ONN-2004/3 area-5) from the western margin (Fig. 1). 2D regional seismic under the National Seismic Program (NSP) covers ~ 50,000 sq. km of unexplored extent of the basin. These seismic lines were acquired with an active spread consisting of 900 channels, with 60 m source and 20 m receiver intervals. The acquired data were processed upto pre-stack time migration.

In addition to newly acquired NSP seismic data, detailed surface geological map produced by Geological Survey of India (GSI), gravity map prepared by ONGC, surface out-crop data and well logs of nine (9) wells, biostratigraphic and lithological information from core data were also integrated to build geological framework in order to establish

the continuity of petroleum system elements in the hitherto unexplored part of the basin.

### Methodology

First part of the adopted workflow (Fig. 4) comprises of gathering information on outcropped sections through published literatures, understanding the pattern of deposition and identifying the depositional breaks within sedimentary successions. Afterward, well log motifs and core data of nine exploratory wells in the western margin were analyzed with the aim of identifying similar sedimentary packages and correlating key geological boundaries across basin. Six major stratigraphic units, namely Basement, Jodhpur group, Bilara/Hanseran Evaporite Group (HEG), Nagaur group, Mesozoic and Tertiary units were identified after integrating outcrop data with available well logs, core and mudlog data. These six key stratigraphic picks were further tied with seismic data and mapped across the study area. Time/depth structural maps for each horizon top and isopach maps of corresponding stratigraphic intervals were generated. The structural framework was prepared to understand the structural development and process of sediment filling in the basin. Detailed analysis on continuity, geometries and amplitudes of seismic reflectors were carried out to define seismic facies and their spatial continuity related to specific stratigraphic interval.

Vertical Seismic Profile (VSP) and/or sonic data of four wells (Bagewala-1, Bajuwala-1, Godu-1 and Punam-1) along with the stack RMS velocity of 16 2D seismic profiles were used to construct velocity model of the basin. Dix conversion (Eq. 1) was performed to convert stack/RMS velocity to interval and then to average velocities along these 2D lines, and interpolated laterally with calibrated well velocity to build a 3D velocity model for depth conversion. All the interpreted time horizons and faults were converted into depth domain to build 3D structural model of the basin. A conceptual depositional model was further constructed primarily by the observations from regional correlation, sedimentological data from the studied wells and seismic datasets with an aim to delineate the elements of the petroleum system, sizes and distributions of probable hydrocarbon accumulations (Dix, 1955)

$$V_{int} = [(t_2 V_{RMS2}^2 - t_1 V_{RMS1}^2) / (t_2 - t_1)]^{1/2} \tag{1}$$

where  $V_{int}$  = Dix interval velocity,  $t_1$  = Two-way travel-time to the first reflector,  $t_2$  = Two-way traveltime to the second reflector,  $V_{RMS1}$  = root-mean-square velocity to the first reflector,  $V_{RMS2}$  = root-mean-square velocity to the second reflector.

### Seismic mapping and stratigraphy

Six horizons namely Basement, Jodhpur Group, Bilara/Hanseran Evaporite Group (HEG), Nagaur group, Mesozoic and Tertiary Top were mapped to identify structural

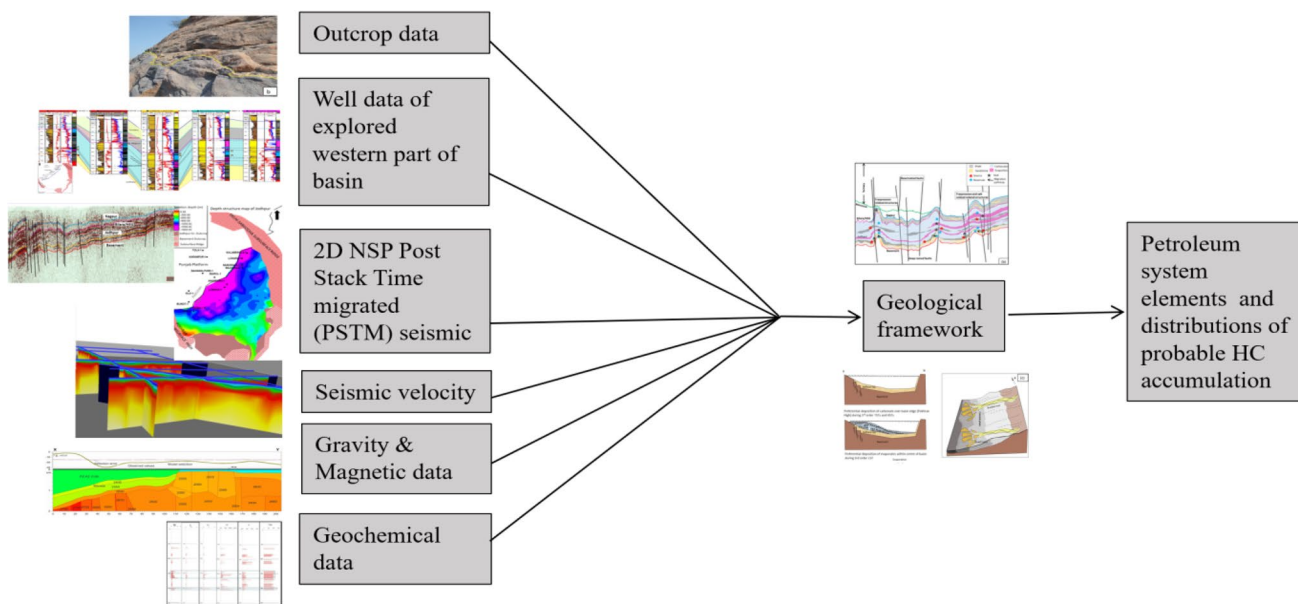
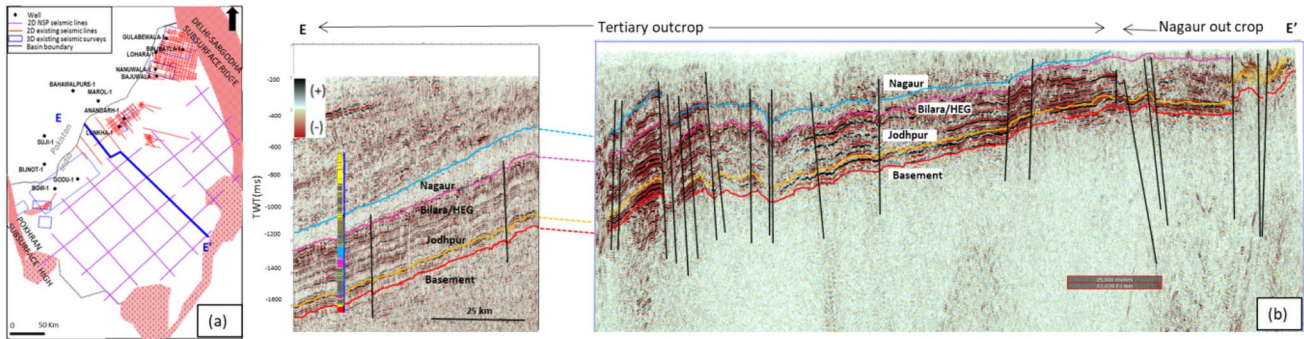


Fig. 4 Generalized workflow used to construct geological framework and accumulation map of Bikaner–Nagaur basin



**Fig. 5** **a** Location map highlights regional cross-section EE' (along dip) through the unexplored part of Bikaner–Nagaur Basin, **b** In this section, Neoproterozoic–Cambrian litho units show compressional structures associated with faults, however, tertiary units remain undeformed

alignment and to locate the prospective areas in the unexplored central-eastern part of the basin. Overall, the basin has thin sediment units (~1 km) with gentle westward dipping litho units (Fig. 5b).

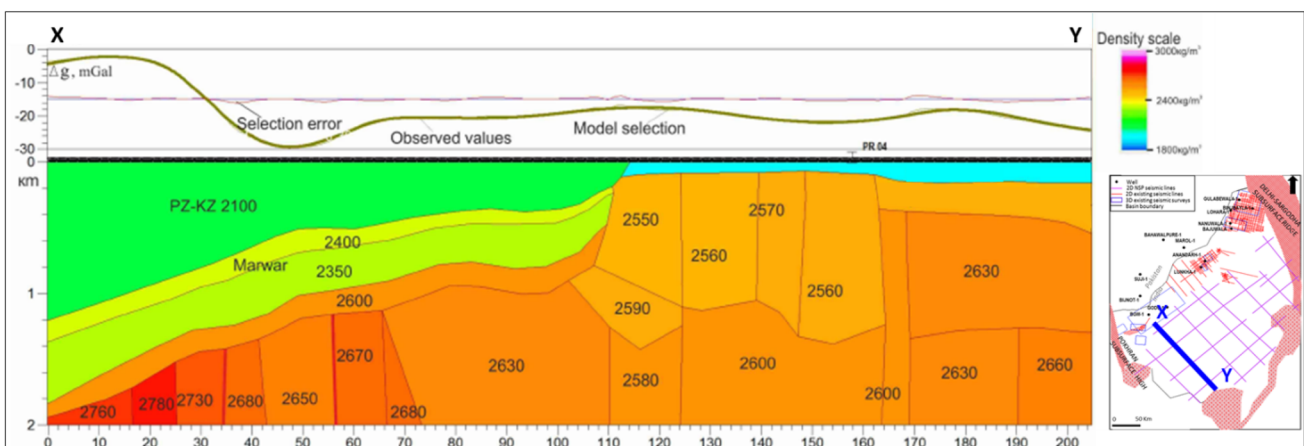
### Basement

Basement is a strong reflector, marked by increase in acoustic impedance (Fig. 5b) and is characterized by varied amplitudes, probably indicating change in lithology from metasediments to volcanics. The gravity model along with the 2D regional NSP line XY (Fig. 6) in the southern boundary of the basin (as per DGH in-house study, 2020) suggested the presence of anisotropy in density within the basement rocks, where the upper layer of the basement possibly referred Malani volcanics with the density of  $2.60 \text{ g/cm}^3$  and the lower layer most likely related to crystalline basement with density ranges between  $2.55$  and  $2.7 \text{ g/cm}^3$ . Regional disposition of the basement showed gentle dip toward the west with maximum depth of around 1850 m

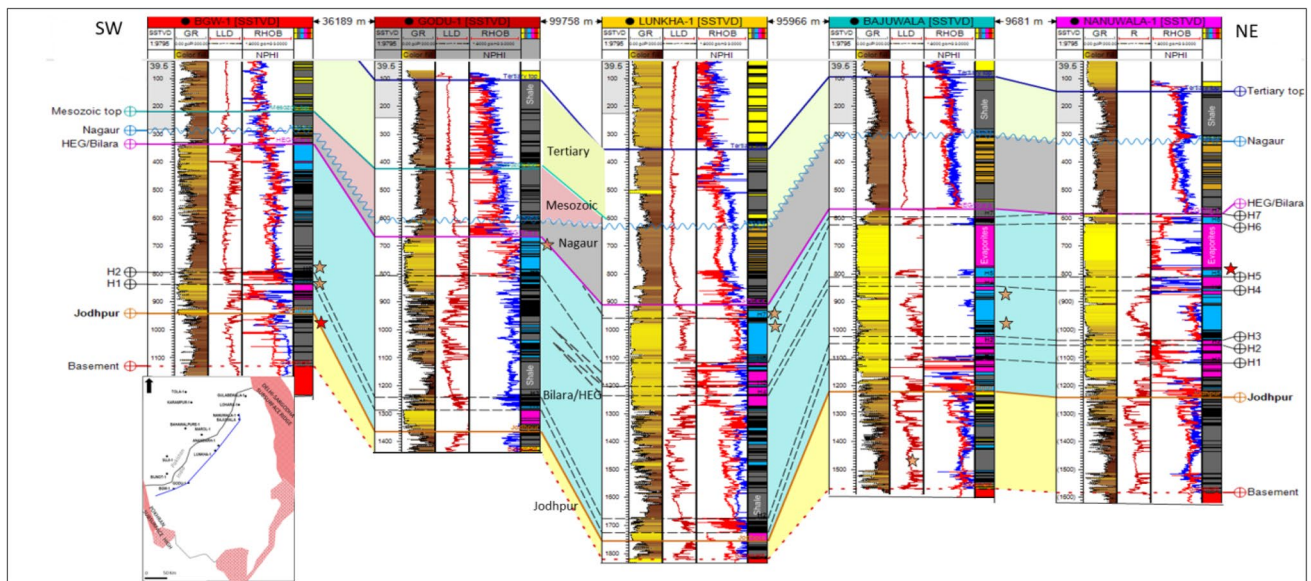
and intersected by five wells namely, Baghewala-1, Godu-1, Lunkha-1, Bajuwala and Nanuwala-1 at the corresponding depths of 1130 m, 1441 m, 1821 m, 1564 m and 1582 m TVDSS (true vertical depth sub-sea), respectively (Fig. 7). However, the average depth of the basement ranges between 900 and 1000 m in the study area (Fig. 11). A series of subparallel north–south and NW–SE trending deep-seated normal faults, related to initial phase of rifting were mapped at the eastern boundary of the basin (Fig. 8). This faulting resulted basement high in east and north-east of the boundary fault.

### Jodhpur group

The deepest sedimentary sequence of Jodhpur group unconformably overlies the basement (Fig. 9b). Jodhpur group predominantly consists of clastic sequence and shows gradational contact with the overlying carbonate-evaporites dominated Bilara/HEG group as observed both in the wells and in outcrops. The reflector is not distinctly identified due



**Fig. 6** Petro-density model illustrates basinal configuration along the NSP line in south-eastern part of the basin. The model depicts sediment thickness of 1–2 km on the top of high density basement



**Fig. 7** Regional correlation through wells in the western margin of Bikaner–Nagaur Basin, intervals produced oil marked in red and hydrocarbon shows are highlighted in orange

to smaller acoustic impedance contrast in seismic, however, the horizon was mapped across the basin with low level of confidence. Internally, the sequence exhibits discontinuous, low frequency reflectors with variation in amplitude which indicates lateral facies variation within this succession (Figs. 5b, 10c). Seismic section along the well Binjbayla-1 in the northern part of the basin, AA' (Fig. 10b) showed possibly stacked, prograding clinoform foresets in the lower part of Jodhpur Group.

Jodhpur group shows onlap against the basement outcrop located in south and south-eastern part of the basin (Fig. 9b). Onlap reflector patterns of Jodhpur sedimentary packages were rarely evident in seismic, however, seismic section along boundary fault, GG' (Fig. 8b, d) shows some onlap patterns at the base of Jodhpur group that indicates Jodhpur group as lowstand systems tract (LST). Lower part of Jodhpur group namely Sonia formation that outcropped along southern boundary of the basin (Fig. 9a), predominantly consists of shale with the localized presence of sand. Upper part of Jodhpur group, Girbhakar formation showed blocky sand sequence and fining upward pattern in both well-log and outcrop, indicating fluvial channel deposits (Fig. 9d). However, channel or channel sets were not identified in the seismic, possibly because the depositional bodies have lower thickness than the resolution of seismic data.

Overall, sedimentary sequence of Jodhpur group followed westward dipping ( $<5^\circ$ ) trend and thickness of the group varies regionally with maximum thickness of around  $\sim 350$  m in the northern part of the basin and gradually became thinner toward the south west (Fig. 12). The average thickness ranges between 200 and 250 m in the unexplored part of

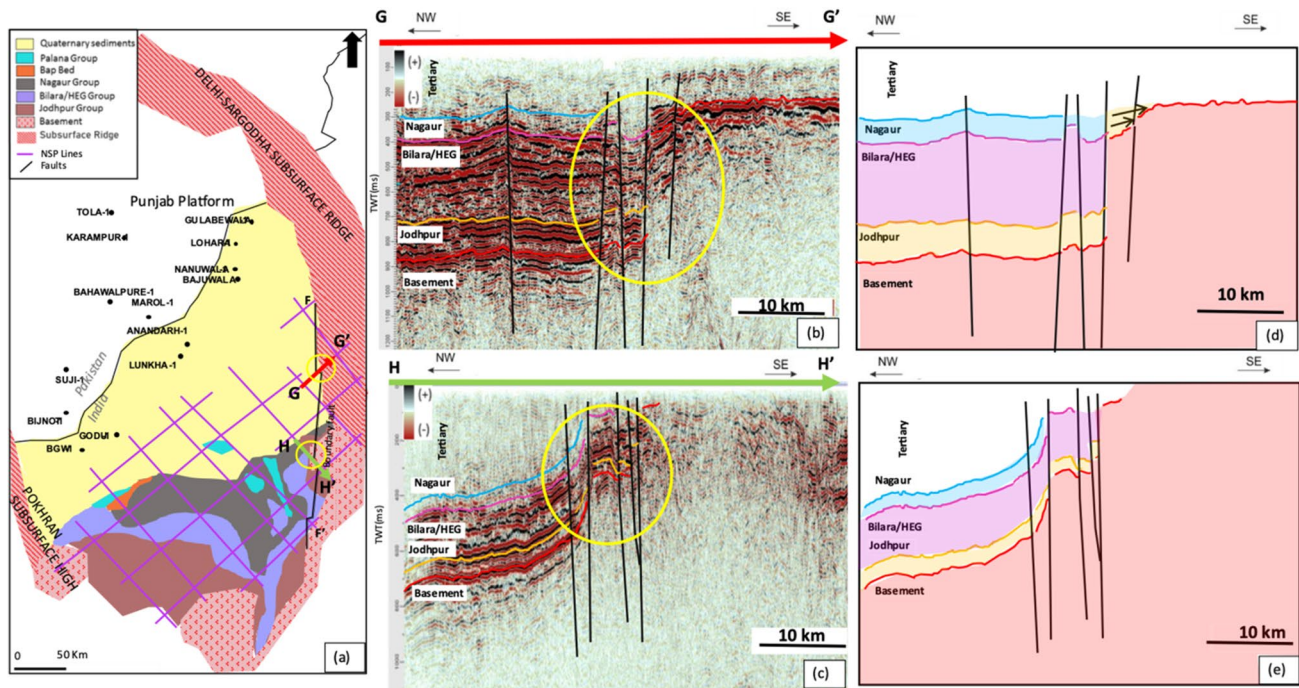
the basin. Variation in thickness of Jodhpur group adjacent to boundary faults and Delhi-Sargodha basement high suggests that deposition of Jodhpur group was synchronous with the fault movement. This evidence indicates there was 'sag phase' during Late Proterozoic time.

Fluvial facies of Jodhpur group are already established as hydrocarbon bearing in wells of Baghewala-1 and Punam-1. The core samples in well Nanuwala-1 shows well-sorted, coarse-grained sandstone with minor quantities of cementing material. Based on the interpretation, average net porosity of Jodhpur sand ranges between 14 and 17% while maximum porosity is recorded as 30% with average thicknesses of sand bed varying between 2 and 8 m.

#### Bilara/Hanseran evaporite group (HEG)

Shallow marine carbonates of Bilara and halites of Hanseran Evaporite Group (HEG) conformably oversteps the Jodhpur group and are overlaid by a younger clastic sequence of Nagaur group across the basin. Top of Bilara/HEG group is related to prominent reflector and the unit was mapped across the basin with good continuity. Internally, the sequence displays high amplitude, continuous and parallel reflectors in the seismic sections (Fig. 13b). The sequence exhibits conformity with overlying and underlying sequences, and follows similar regional trend. Thickness of the group varies regionally and gradually becomes thinner in the central-eastern part of the basin with thickness ranges between 300 and 400 m (Fig. 12).

The Bilara group predominantly consists of limestone, algal dolomites and stromatolitic limestone as observed in



**Fig. 8** a Outcrop map of Bikaner–Nagaur basin. Seismic sections GG' and HH' are marked in base map. b–e Depict seismic and schematic cross sections across the boundary fault that show maximum displacements upto 400 m

wells and outcrops (Fig. 10f). The sequence was most likely deposited during marine transgression over the flooded rift margins as platform carbonates and is interpreted as TST (Fig. 14). Presence of Bilara group is limited to the southern and eastern part of the basin suggesting these areas as basin margin, whereas the time equivalent Hanseran Evaporite Group (HEG) consisting of cyclic deposits of halite (dominant constituent) with intervening zones of potash minerals, anhydrite and dolomite, are found in the northern part of the basin. Deposition of the halites and anhydrites during periodic LST is interpreted within center of the basin further away from the entrance of sea water. Hence, configuration of the basin remained shallower in the south-eastern part and gradually deepen toward the north during early Cambrian (Fig. 14).

Seven cycles of evaporite (H1–H7 halites) were reported based on the evidence from parametric wells drilled by Geological Survey of India (Kumar et al. 2005). The same seven cycles of halites were recognized by low GR, high resistivity, and very low density log motif and also identified in wells of Nanuwala-1, Bajuwala-1, Ramawali-1, Lohara-1 and Gulabewala-1 which were located in northern part of the basin (Fig. 7). Lower two cycles of evaporates, namely, H1 and H2 were regionally extensive and were identified in all the wells across the basin. Thickness of the two lower halite cycles ranges between 10 and 30 m whereas the thickness of upper halites (H3–H7) varies between 30 and 150 m. The HEG halite unit acts as an effective top seal

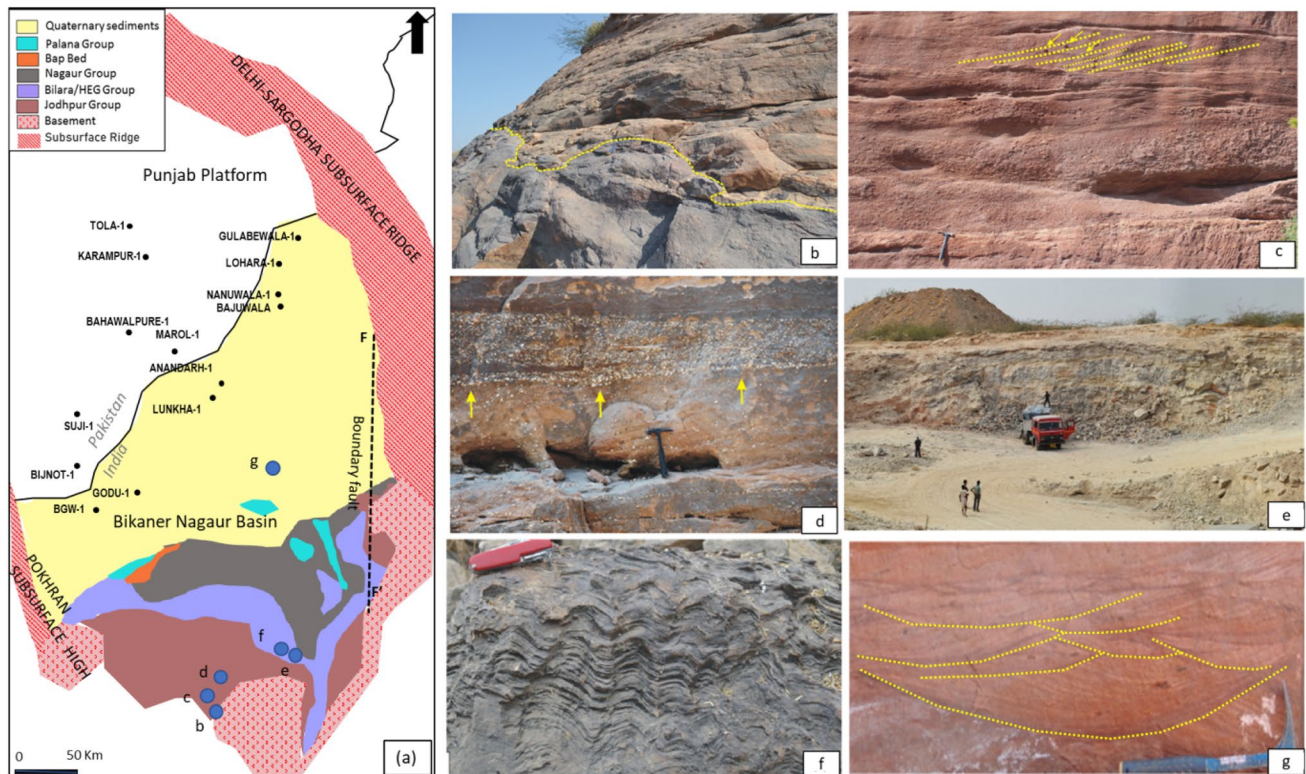
for reservoirs within Jodhpur and Bilara group. Dolomites and limestones within Bilara/HEG group are compact with average porosities of 8–9%. However, porosity data indicates quality of the reservoir is largely dependent on the presence of fractures within the carbonates. Geochemical analysis of multiple oil samples reported from the wells of Nanuwala-1, Baghewala-1, Lohara-1, Ramawali-1 and Bajuwala-1 are mostly from the fractured carbonate zones.

Geochemical analysis of core samples and core photographs (Fig. 15b) of wells Punam-1, Shekhra-1, Charanwala-1, Baghewala-1 and Baghewala-5 confirms organic rich laminated dolomites and argillaceous units in lower Bilara as proven source. Similar organic rich carbonate and stromatolitic sequence (Fig. 10f) have been identified in outcrop exposure of lower Bilara group in southern part of the basin, which establishes existence of laminated dolomite/argillaceous source in the unexplored part of the basin.

### Nagaur group

Clastic dominated Nagaur group conformably overlies above the Bilara/HEG group. Base of the Nagaur group predominantly consists of argillaceous with limited presence of coarse grain sandstone (Fig. 10g) as evident from both the outcrop and well data. However, the upper part of Nagaur group primarily is composed of siltstone with thin, fining upward sandstone layer and interpreted as continental fluvial environment. Outcrop evidence of trace fossils of trilobites





**Fig. 9** **a** Geological map showing litho-boundaries in Bikaner–Nagaur basin. **b** Sonia Sandstone shows onlap (marked by yellow arrow) against the Malani Group of rocks. **c** Large scale cross bedding with different size nodules in sandstone facies of Sonia formation in Jodhpur Group. **d** Gravels, cobbles dominated upper Jodhpur Group. **e** Limestone Quarry in Gotan Limestone near Pundlu. **f** Stromatolite within Bilara Limestone. **g** Trough cross bedding within Nagaur sandstone exposed in Dulmera quarry (modified after Sharma et al. 2014)

(*Cruziana*, *Dimorphichnus* and *Rusophycus*) from the upper part of Nagaur sandstone confirms the age as Cambrian (Kumar et al. 2008).

In seismic section, Nagaur group is marked by weak contrast in acoustic impedance and characterized by low amplitude and discontinuous reflectors. The thickness of the unit varies between 50 and 250 m and is gradually pinched out toward the south-western part of the basin (Fig. 12). Continuity of Nagaur group was mapped in the unexplored region, however, Nagaur group mostly outcropped in the eastern part of the basin as shown in Fig. 8d.

### Bap boulder bed and Mesozoic sediments

Post deposition period of Nagaur group, the basin underwent long depositional hiatus during Ordovician, Silurian and Devonian time (Fig. 3). Deposition of sedimentation initiated again during Permo-Carboniferous time. Permo-Carboniferous Bap Boulder bed positioned unconformably over the Nagaur group. Presence of Bap Boulder bed is highly restricted to the south western part of the basin adjacent to Pokhran high and the succession is overlain by

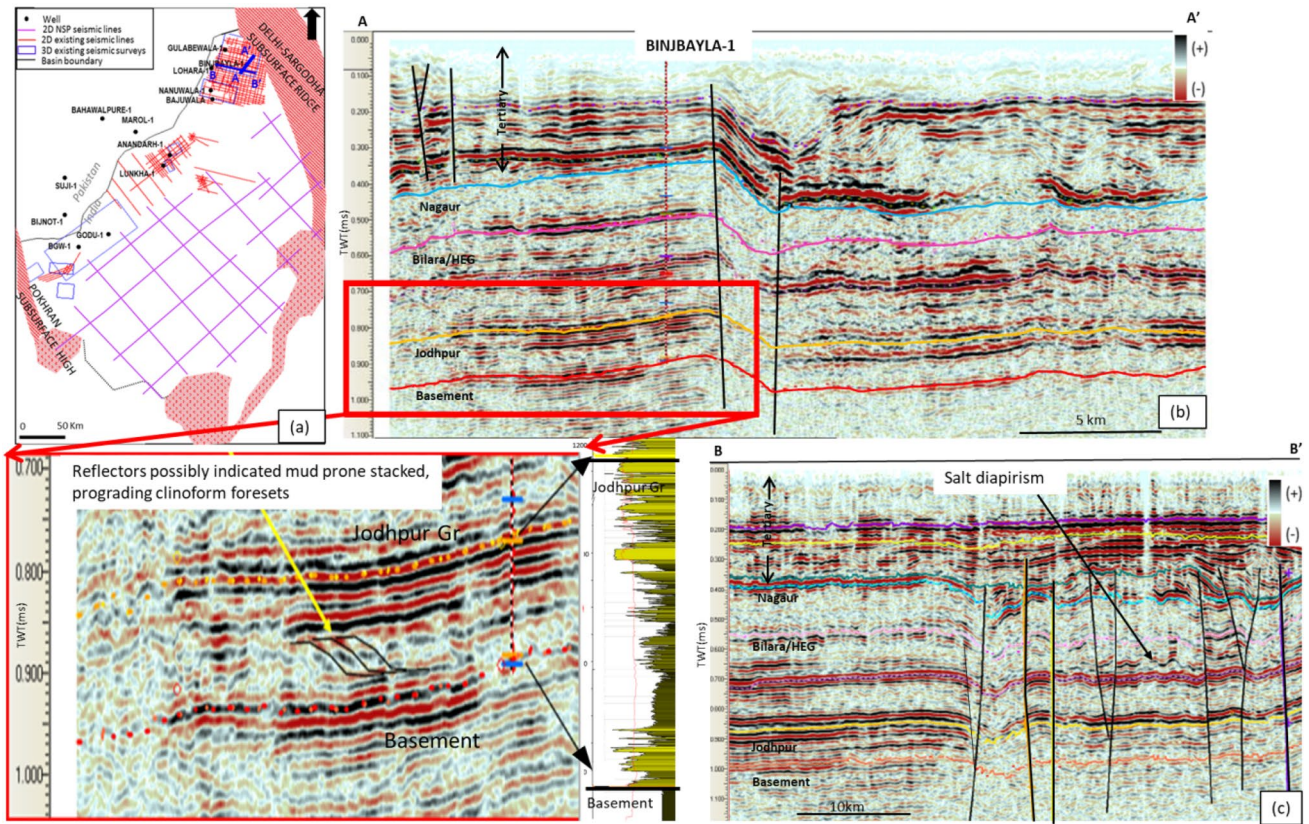
argillaceous marine sequence of Mesozoic age. Similar to Bap bed, presence of Mesozoic succession restricted to the southwestern part of basin.

### Tertiary sedimentation

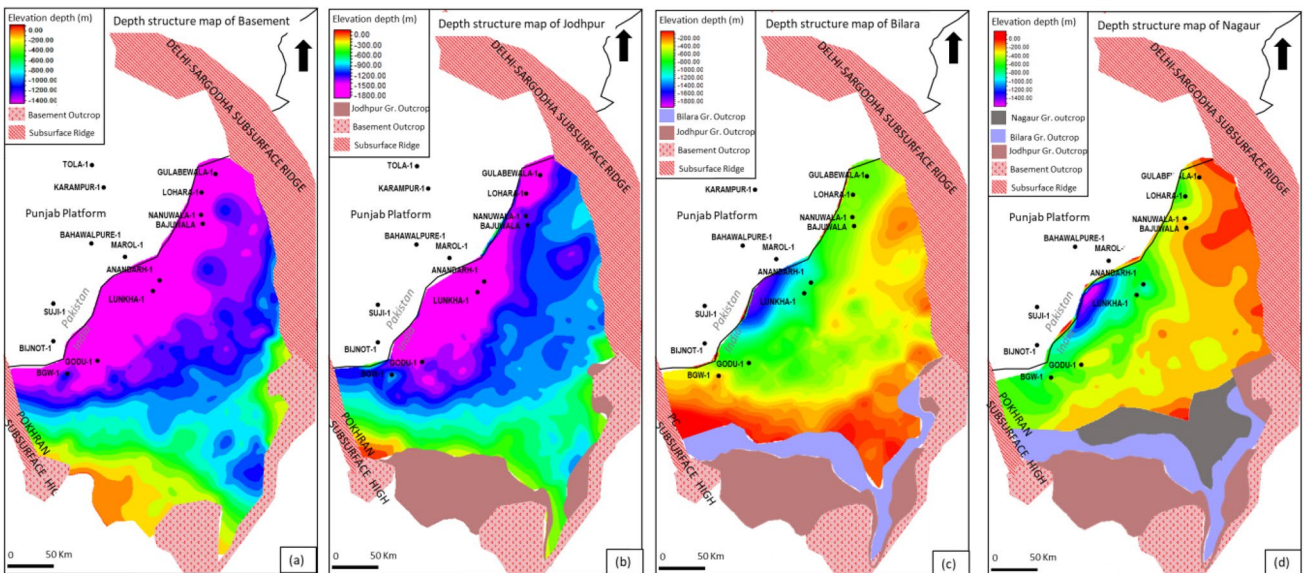
Tertiary unit (Fig. 3) is composed of Palana, Marh and Jogiria formation with maximum thickness recorded upto 287 m in the outcrop (Kumar et al. 2005). Tertiary litho-units are unconformably overlying Mesozoic rocks in the south-western part of the basin whereas the units unconformably lie above the Neoproterozoic-Cambrian succession in the central and northern parts. Tertiary sediments are mostly covered by Quaternary alluvium throughout the basin with average thickness ranges between 300 and 500 m.

### Structural analysis and possible trapping mechanism

The eastern margin of the basin is bounded by north–south trending boundary faults (Fig. 8a). 3D seismic data from the northern and south-western regions confirm the presence of



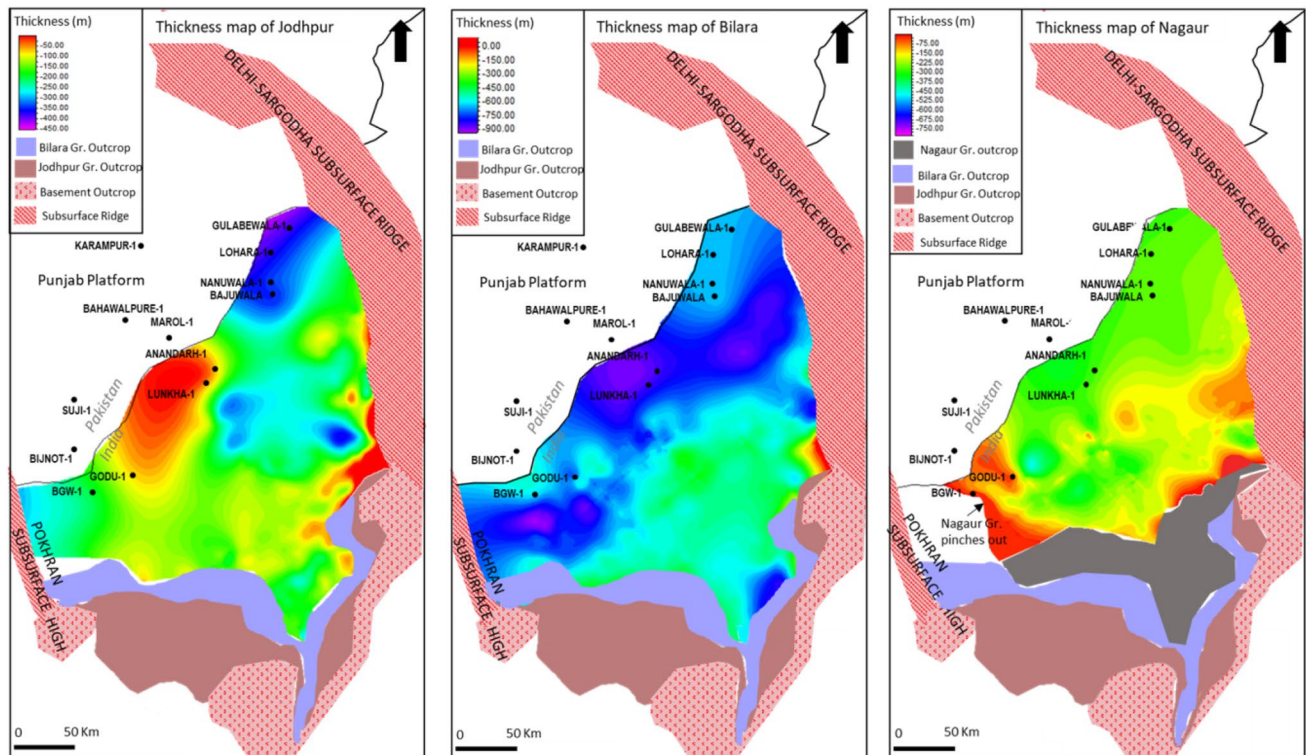
**Fig. 10** a Map highlights location of AA' and BB' seismic sections, b AA' seismic section along well BINJBAYLA-1 shows possibly clinoform foresets in lower part of Jodhpur Group, c BB' seismic section shows small scale salt diapiric structures within HEG/Bilara halites



**Fig. 11** Depth structure maps of Basement (a), Jodhpur group (b), Bilara group (c) and Nagaur group (d)

two other predominant sets of faults system trending along NNE-SSW and NNW-SSE directions (Fig. 16a). Sparse 2D

seismic data are available for central and eastern part of the basin, therefore, the predicted orientation of the faults has



**Fig. 12** Thickness maps of Jodhpur group (a), Bilara group (b) and Nagaur group (c)

higher range of uncertainty than that of the interpretation projected from the 3D seismic data.

Most of the faults in the basin were extended deeper underneath the subsurface and were resulted by initial phase of rifting during Late Proterozoic. These faults were often aligned in en-echelon pattern and formed a series of horst and graben structures (Fig. 5b). Throw of the faults measures up to 50 m, however, the faults located close to the boundary fault showed maximum displacement of 200–400 m (Fig. 9).

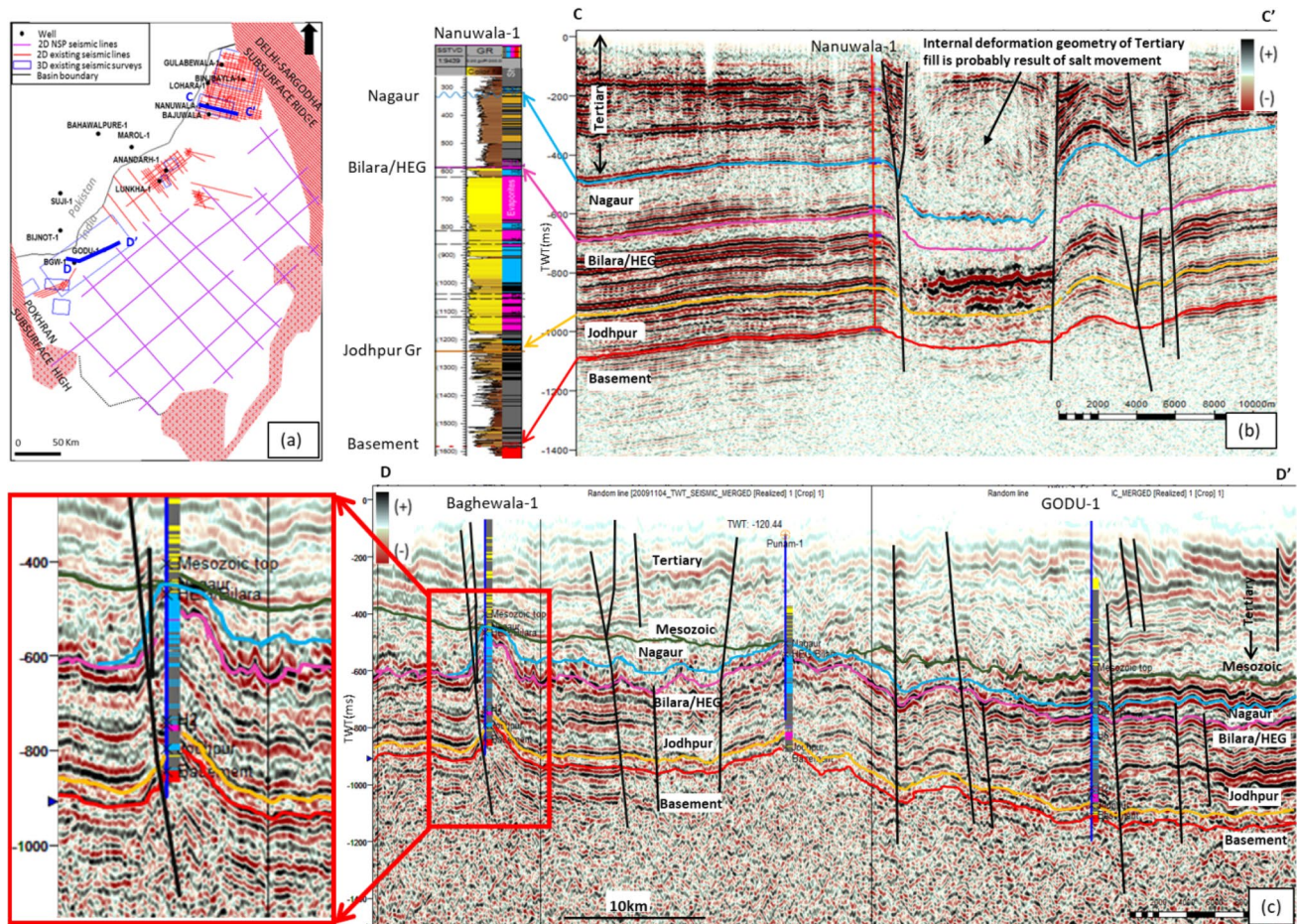
Faults in the northern part of the basin witnessed multiple phases of reactivation due to younger tectonic episodes such as extension during Permo-Triassic, early-to-mid Jurassic and compression during tertiary time. The changes in dip-slip movement across the steeply dipping fault plane and the presence of splay within the shallow depth succession are the key indicators of reactivation of the fault system (Fig. 13b). Splays in the shallow depth section are often associated with these deep-rooted faults and showed limited vertical displacement with significant presence of internal deformation within the tertiary sequence. Two types of anticlinal structures were observed in the northern part and were discussed below.

Subtle and small scale anticlinal structures related to salt diapirism (Fig. 6c) were spotted in the region within the relatively thick halite sequence. Seismic section CC' in Fig. 13b shows the presence of internal deformations of

tertiary deposits resulted due to salt movement during the tertiary compression. Other set of compressional structures were observed across the high angle, deep seated NNE-SSW and NNW-SSE trending faults. This compression-induced deformation is possibly linked with the Tertiary compression as the structures were evident at all the depth levels (Fig. 13b) throughout the northern region, however, the possibility of presence of hydrocarbon is not significant within these structures as the trap mostly formed considerably later than the period of HC expulsion.

South-western part of the basin is dominated by deep-seated NNE-SSW trending sub-parallel faults. Anticlinal structures were spotted in patches and were primarily bounded by the major fault systems. These anticlines are genetically correlated with the Cambrian compression and were confined to Neoproterozoic-Cambrian level only (Fig. 13c). These fault bounded anticlinal structures are proven hydrocarbon accumulations with dimension ranges between 10 and 50 sq.km viz., Baghewala (Fig. 13c), Tuvriwala, Punam structures. Shallow depth sections were mostly undeformed with presence of some minor faults.

Similar types of anticlinal structures were also identified in the unexplored part of basin (Fig. 17), tertiary sediments were mostly undeformed and the size of these structures vary within the range of 30–100 sq. km (Fig. 16). The exact size and shape of these possible entrapments may differ as



**Fig. 13** **a** Map highlights location of CC' and DD' seismic sections, **b** CC' seismic section along well NANUWALA-1 shows major apparent dip-slip movement across steep dip, deep-rooted fault planes. Lower-angle splays in the shallow section show more deformation with less apparent vertical displacement. Internal deformation

within Tertiary fill probably resulted due to salt movement, **c** DD' seismic section along Baghewala-1 and Godu-1 shows compressional structures bounded by steep dip faults. Thickness of Nagaur group gradually thinning toward south west and pinches out near Baghewala structure, whereas Mesozoic section thins out toward north east

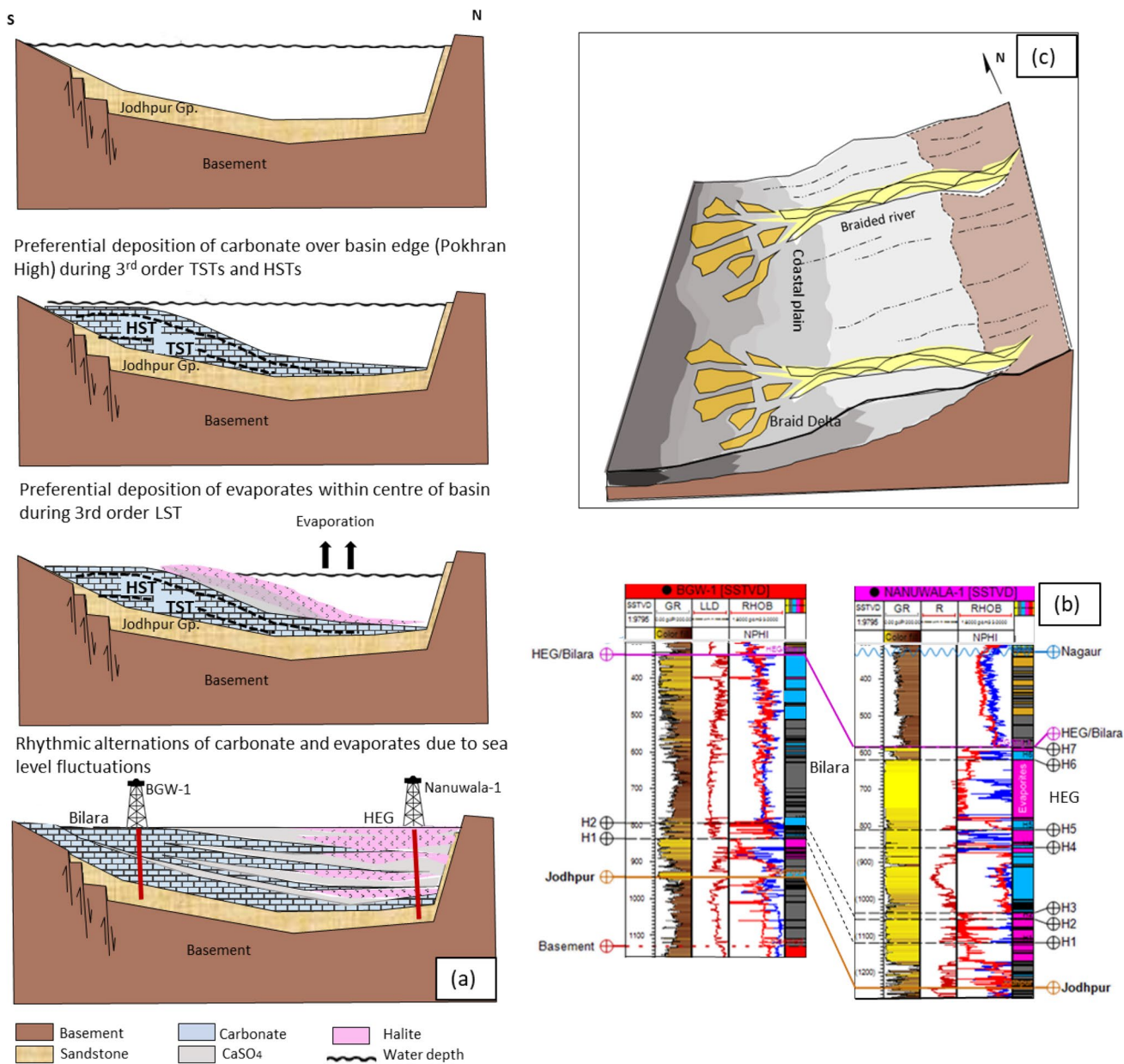
the available seismic data is sparse with 2D seismic lines separated by approximately 50 km apart.

The thickness of the sand layer in Jodhpur group is 2–10 m with overall sand to shale ratio is 20:80 whereas Bilara/HEG dolomite reservoir is 10–20 m thick and overall reservoir to non-reservoir (halite and shale) ratio is 30:70. Therefore, the faults in the southern and unexplored part of the basin are expected to be sealing in nature due to the presence of significant quantity of impermeable litho units (shale/halite) within both the formations across the faults which have throw of around 40–50 m. However, detailed mechanisms of fault seal analysis were not been carried out due to paucity of well data adjacent and across the faults. Lithology information of the wells located far away from the faults were not considered for the fault juxtaposition analysis as variation of facies is expected to occur regionally. Additionally, a considerable amount of uncertainty may be expected to exist while calculating fault throw due to

lack of well control in the calibrated seismic velocity data, which was used to convert interpreted horizons and faults from time domain to depth domain. Therefore, the analysis was carried out in order to define sealing capacity of faults. Evidences of reactivation of the faults were already identified in some part of the basin, which may cause the possible risk of seal failure associated with hydrocarbon entrapments.

### Hydrocarbon source and migration

Heavy oil (17.6°API) discovered from Baghewala-1 well from the interval of 1104–1117 m depth within Jodhpur group is sulphur rich (> 1%S) and low in thermal maturity (Craig et al. 2009). Geochemical characteristics of Baghewala oil suggests algal or bacterial organic matter as likely source, which were deposited under anoxic condition (Peters et al. 1995). Rock eval data of five wells further indicates presence of marginally mature source rock (Ro ranges



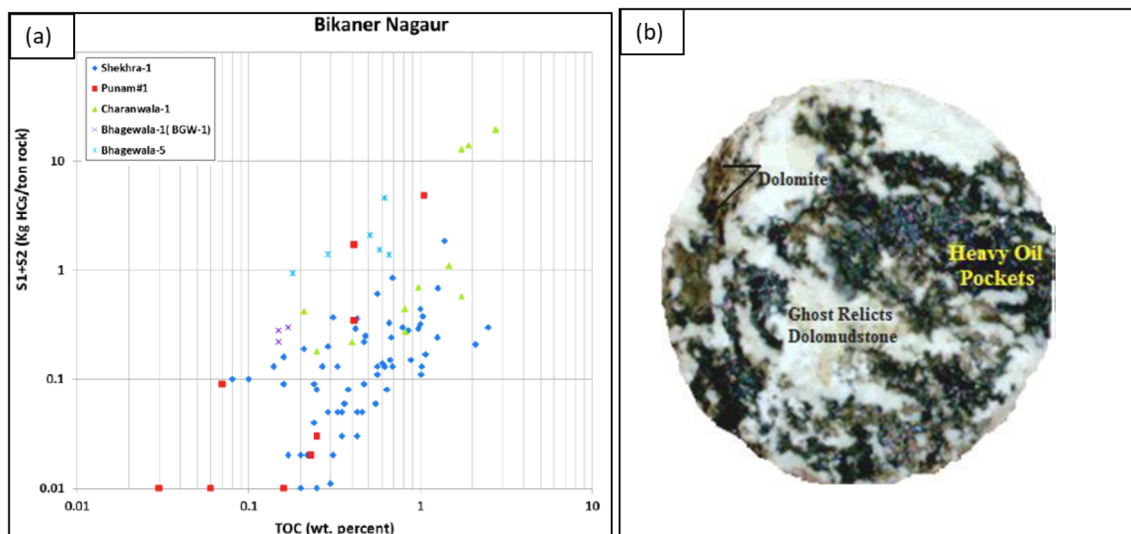
**Fig. 14** a Depositional environment and basin configuration during deposition of Bilara carbonate/age equivalence HEG halite, b Lateral facies variation from Bilara limestone to HEG halites are correlated across wells, where well located in southern part of basin BGW-1

shows presence thick limestone layers and Nanuwala-1 located in northern part shows predominant presence of halite layers, c conceptualized depositional model of Jodhpur group

0.5–0.7%) with poor to moderate organic content (0.17–2.75 wt% TOC) and hydrogen index up to 400 mg/g TOC, typical oil prone organic matter (DGH Internal Report, 2017, Peters et al. 1995) deposited in intertidal flat stromatolites (Cozzi et al. 2012) and marine carbonate succession (Fig. 15).

Regional stratigraphic correlation indicates existence of primary source organic rich laminated carbonates and stromatolite layers in lower Bilara group throughout the basin. Directorate General of Hydrocarbons (DGH) carried out 3D Petroleum system model for western part of

Bikaner–Nagaur basin. Based on the model, peak time for hydrocarbon expulsion is estimated as early Mesozoic time (Fig. 18) and in situ generation or short distance migration from source are estimated as potential mechanism of hydrocarbon migration.



**Fig. 15** **a** Total generation potential versus TOC plot for Bilara group in Bikaner–Nagaur basin, **b** transverse slice of core displays dolomite hosting heavy oil pockets in Bilara group

### Probable petroleum system of central and eastern part of Bikaner–Nagaur basin

Petroleum system in this unexplored part of the basin has been speculated based on the seismic facies and stratigraphic framework study.

#### Neo-proterozoic Jodhpur play

Discovery of heavy oil in Baghewala-1 opened up the hydrocarbon potential of Cambrian Jodhpur clastic play in the western margin of the basin. However, the study envisages the existence of the play concept in unexplored central and eastern part of the basin where the thickness of Jodhpur group is attaining around 200–250 m.

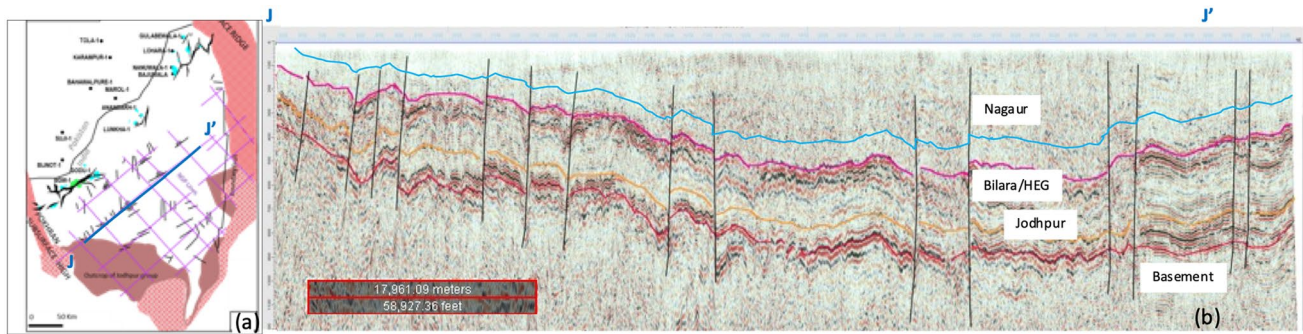
Presence of fluvio-deltaic sandstone within the Jodhpur group with moderate to good reservoir potential is identified in the study area. These reservoirs are expected to be charged by organic rich laminated dolomites and argillaceous beds within lower Bilara/HEG group.

Regionally widespread halite cycles (H1 and H2) of lower Bilara/HEG group are interpreted to be acting as effective top seal for the Jodhpur reservoirs. Structurally controlled entrapment, NNE–SSW trending fault bounded anticlinal structures similar to proven hydrocarbon accumulation were mapped in the study area. These elongated anticlinal structures are related to Cambrian compression and might act as possible traps. Eight such stacked leads were identified with size ranging between 30 and 100 sq. km. Considerable amount of uncertainty remains in the size of the structures primarily due to sparseness of 2D lines. Favorable structural setup like fault juxtaposition of overlying source against

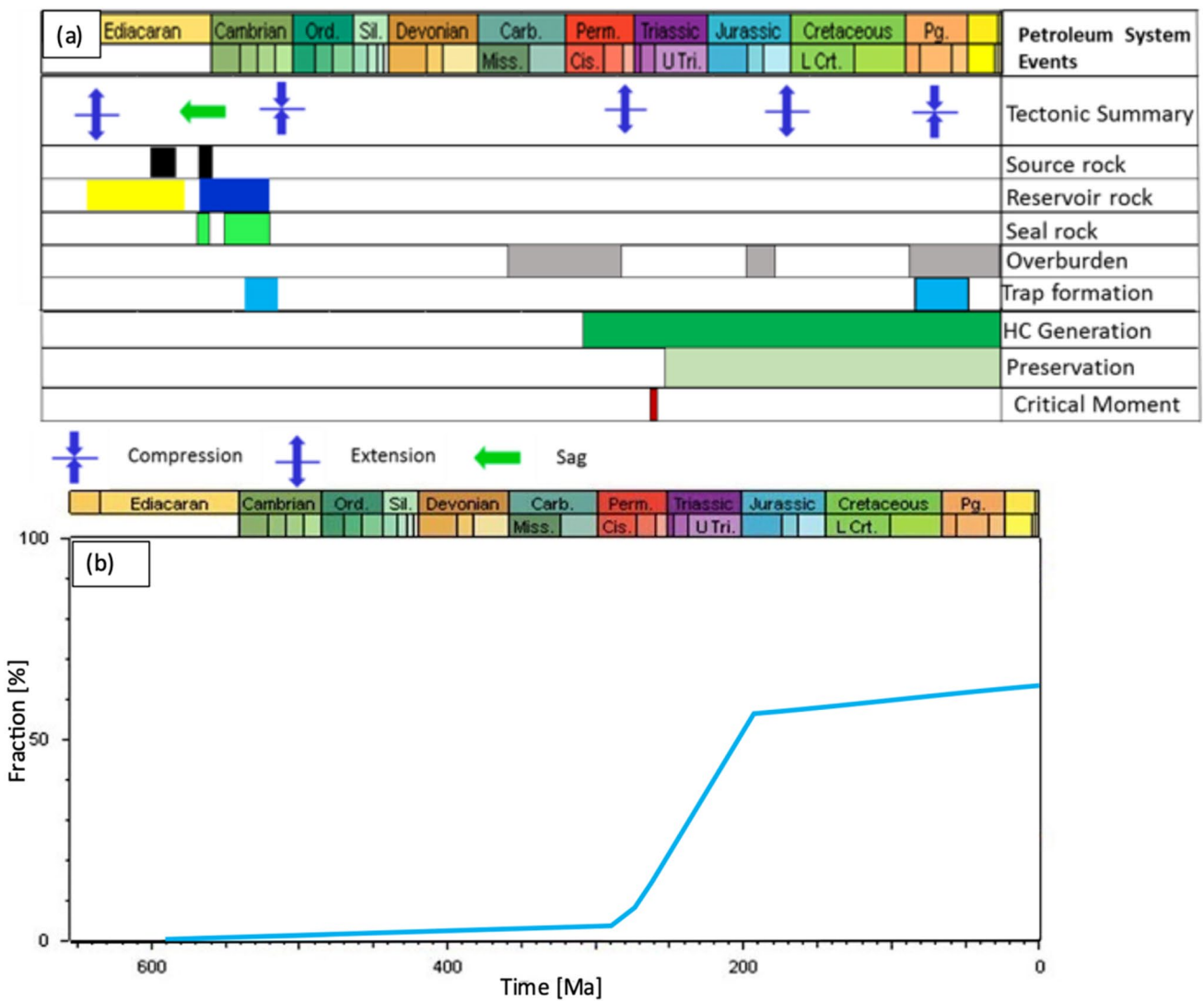
Jodhpur reservoir and presence of effective top seal are essential to charge the Jodhpur traps. Quality of the source rock and failure of sealing due to fault reactivation are identified as the probable risks associated with these leads. However, no fault seal analysis has been carried out in this study. The inference is purely suggestive and conjectural in nature.

#### Cambrian Bilara/HEG play

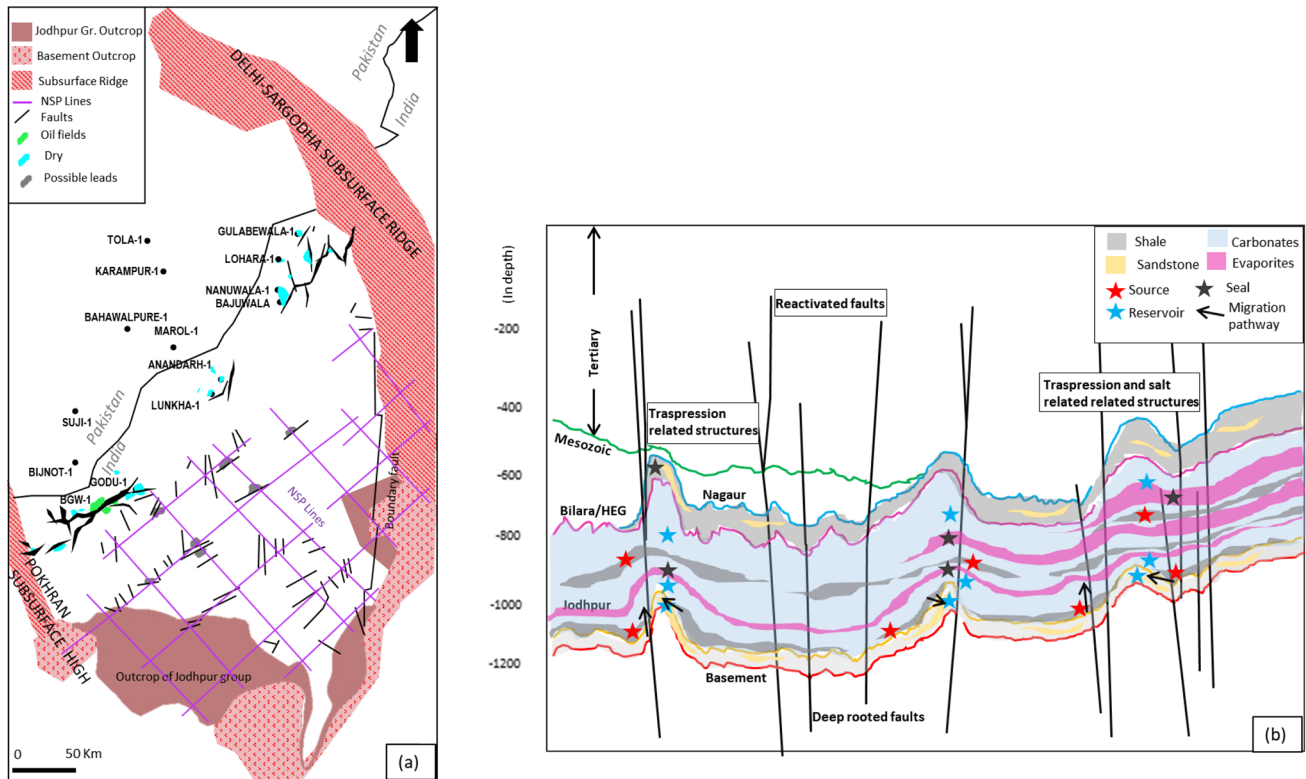
Similar to Cambrian Jodhpur play, presence of hydrocarbon in the Bilara/HEG group evident from wells Godu-1, Lunkha-1 and Bajuwala-1 broaden the potential for new exploration in this basin. Maximum thickness up to 400 m of Bilara group is envisaged in the study area. Shallow marine fractured dolomitic intervals within Bilara group are identified as potential reservoir in the study area. However, the quality of reservoir is largely dependent on the intensity of the fractures within the dolomites. Presence of laminated dolomites as well as organic rich argillaceous source were correlated across the unexplored part of the basin which might charge dolomitic reservoirs through short distances migration. Both the regionally extensive lower halite layers (H1–H2) and regionally restricted upper halite layers (H3–H6) might act as effective top seal depending on the position of the reservoir rock. Fault bounded elongated anticlinal structures associated with Cambrian compression form possible traps similar to Jodhpur play. Quality of the source rock and fault seal failure is speculated as potential risk associated with eight identified leads. Again, no fault seal analysis has been carried out in this study.



**Fig. 16** **a** Location map highlights regional cross-section JJ' (along Strike) through the unexplored part of Bikaner–Nagaur Basin, **b** seismic section shows series of compressional structures bounded by steep dip faults



**Fig. 17** **a** Event chart of Petroleum systems of Bikaner–Nagaur basin, **b** transformation ratio of Bilara carbonate which is main source rock in this basin; figure depicts main hydrocarbon expulsion window is Permo-Triassic time (DGH 2017)



**Fig. 18** **a** Location map shows discoveries, dry targets in western margin and possible leads in unexplored part of Bikaner–Nagaur basin, **b** conceptual model of Neoproterozoic–Cambrian petroleum system of Bikaner–Nagaur basin

## Conclusions

The following main conclusions are drawn from this study of the central and eastern part of Bikaner–Nagaur basin:

- Knowledge of central and eastern part of the basin was earlier limited due to lack of subsurface data. 2D seismic data acquired for the first time under National Seismic Program (NSP) unlocks the opportunity for understanding of subsurface in this area. Six major reflectors and dominant structural elements were mapped on these 2D seismic data by integrating well log, core and outcrop data.
- Two Neoproterozoic–Cambrian plays, namely, Jodhpur and overlying Bilara Group/Hanseran Evaporite Group (HEG) are envisaged in the study area of the basin. Presence of reservoir equivalent facies in fluviodeltaic sandstone of Jodhpur and fractured dolomites of Bilara/HEG group are established in this area. Continuity of the lower Halite cycles (H1 and H2), top seal for the Jodhpur and lower Bilara reservoir were mapped across the area. However, upper halite cycles, interpreted as plausible seal for upper Bilara dolomite reservoirs, were found to be restricted in the northern part of the basin. Organic rich laminated dolomites and argillaceous litho-units within lower Bilara/HEG group spotted in the wells were correlated with the outcrops and presence of moderate quality of source rock is predicted in the unexplored part of basin.
- Hydrocarbon pools associated with the discovery of wells namely Baghewala-1, Punam-1 are fault bounded anticlinal structures caused by Cambrian compression. Cambrian structures were likely to be charged if Jodhpur reservoir juxtaposed against Bilara/HEG kitchen across the fault plane, while Bilara/HEG reservoirs were charged by short distance migration from the local kitchen. Anticlinal structures, developed due to tertiary compression, identified in northern part of the basin might not be charged as trap formation was much later than the timing of expulsion of hydrocarbons. Cambrian compressional anticlines were identified on sparse 2D NSP seismic lines in the area at around equivalent depth range from where Baghewala-1 oil flowed. Size of the anticlines range in 30–200 sq. km area. Detailed 2D followed by 3D survey are recommended to better delineate the prospect and reduce the uncertainty in delimiting the areal extent.
- Reactivation of pre-existing faults are common in the basin and might enhance the risk of trap failure for the



anticlinal structures associated with faults. However, no fault/trap seal analysis was carried out in this study.

- The study helps to develop reasonable understanding on the presence and distribution of elements of petroleum system throughout central and eastern part of Bikaner–Nagaur basin. Outcome of the study will assist future exploration activities in this vast region which was previously unexplored.

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