Journal of Petroleum Exploration and Production Technology (2023) 13:1979–1992
https://doi.org/10.1007/s13202-023-01638-x

DISCUSSION

Discussion "Structural analysis and seismic stratigraphy for delineation of Neoproterozoic–Cambrian petroleum system in central and eastern part of Bikaner–Nagaur basin, India" by A. Mandal, D. Saha and A. Kumar, Journal of Petroleum Exploration and Production Technology, 2021, p. 1–17 (https://doi.org/10.1007/s13202-0210-01432-7)

L. R. Chowdhary[1]

Received: 20 July 2022 / Accepted: 21 April 2023 / Published online: 1 June 2023

Mandal, Saha and Kumar (2021) have analyzed well log motifs and core data of 9 exploratory wells located in the western part of the Bikaner–Naguar Basin with the aim of identifying similar sedimentary packages and correlating key geological boundaries across the basin. For this purpose, they identified six major stratigraphic units, namely Basement, Jodhpur, Bilara/Hanseran Evaporite (HEG) and Nagaur formations[1], and Mesozoic and Tertiary (Fig. 1), integrating outcrop data with available well logs, core and mud log data. The authors then tied up these six stratigraphic units with seismic data and mapped across the study area and then generated time/depth structural maps for each horizon top and isopach map of corresponding stratigraphic intervals. Finally, the authors prepared the structural framework of the basin to understand the structural development and process of sedimentary filling of the basin.

But unfortunately, the entire information generated and conclusions drawn by the authors is based on misidentification of the six stratigraphic units, the basis for generating time/depth and isopach maps for the six stratigraphic units and for preparing structural framework for understanding the structural development and sedimentary filling processes in the basin.

Following the discovery of heavy oil in Baghewala structure in 1991 by Oil India in Bikaner–Nagaur Basin, the basin has been a subject of study by several workers from oil industry, Geological Survey of India and academia; of particular interest to this discussion are two papers:

- Das Gupta and Bulgauda (1994) of Oil India giving an overview of geology and hydrocarbon occurrences in the Bikaner–Naguar Basin and.
- Peters et al (1995) discussing the Infracambrian source rock based on biomarkers in the Baghewala-1 oil.

Peters et al. (1995, Fig. 2) in his paper included generalized stratigraphic column of the Baghewala-1 well giving lithology of each rock unit and their formation tops. Das Gupta and Bulgauda (1994; Figure 7) published a tentative electric log correlation of Baghewala-1 and Kalrewala-2 wells giving the formation tops of the stratigraphic units penetrated by these two wells.

The generalized stratigraphic column of the Baghewala-1 well after Peters et al. (1995) and the formation tops in electric log of the well after Das Gupta and Bulgauda (1994) is given in Fig. 2a and b. The lithology of the rock units in the stratigraphic column match with the electric log motifs of the well. The formation tops for the Baghewala-1 well by Mandal, Saha and Kumar are given in Fig. 2c and none of the stratigraphic boundaries of the rock units (formation tops), except the top of Jodhpur Formation, match or coincide with the lithologies in the stratigraphic column of the well.

The Neoproterozoic–Cambrian sequence drilled in Bijnot-1 well in Punjab platform has also been correlated with Baghewala-1 and Kalrewala-2 wells (Fig. 3) by Raza et al. (2008). The formation tops in Bijnot-1 well conform with and confirm the formation tops given by Das Gupta and Bulgauda (1994) and Peters et al. (1995).

This comment refers to the article available online at https://doi.org/10.1007/s13202-021-01432-7.

This is a Discussion by L. R. Chowdhary, on a published manuscript, PEPT-D-20-00538R2 and the subsequent Authors' responses and rebuttals.

✉ L. R. Chowdhary

[1] Longwood, USA

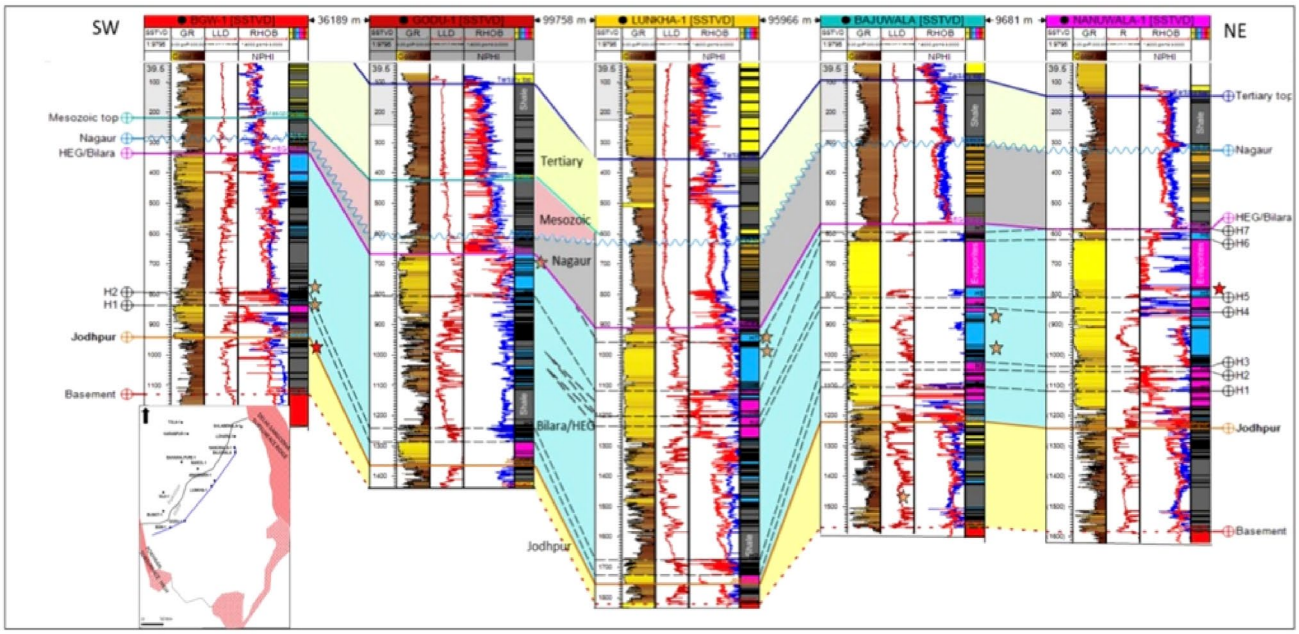

Fig. 1 Regional correlation through Baghewala-1, Godu-1, Lunkha-1, Bajuwala-1 and Nanuwala-1 wells, located in the western part of the Bikaner–Nagaur Basin showing stratigraphic boundaries. Depths subsea TVD (modified after Mandal et al. 2021)

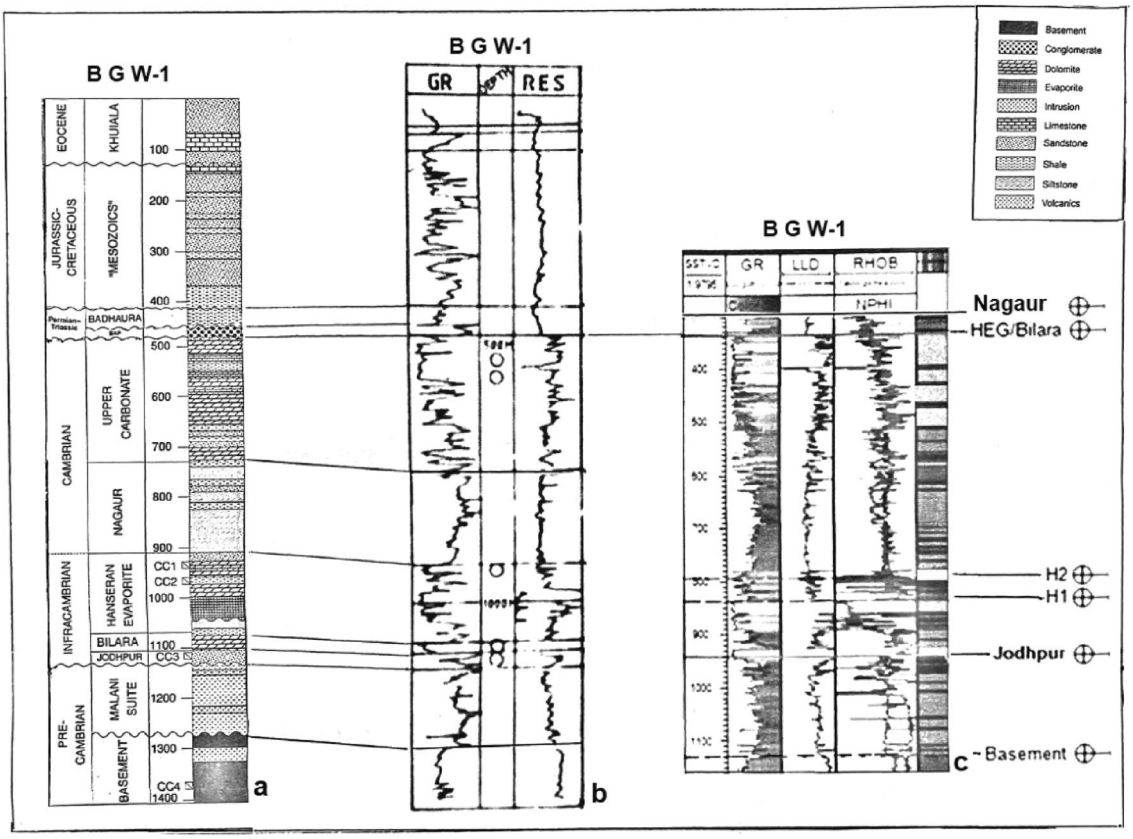

Fig. 2 Baghewala (BGW)-1 well a. Generalized stratigraphic column (modified after Peters et al. 1995); **b** Formation tops on electric logs after Das Gupta and Bulgauda (1994); **c** Formation tops onelectric logs after Mandal et al. (2021). Depths in Figs. 2a and 2b are log depths and in Fig. 2c are subsea TVD

Mandal, Saha and Kumar (2021) referred to the papers of Das Gupta and Bulgauda (1994) and Peters et al. (1995) but disregarded their stratigraphic boundaries and generated new stratigraphic tops without any basis. Baghewwala-1 well was drilled by Oil India as the first exploration well in the basin and Das Gupta and Bulgauda working in Oil India had ample information about the well, and had the opportunity to study and integrate core and mud log data and tie up formation tops with well logs to generate stratigraphic column of the well. Therefore, the formation boundaries given@ by workers of the operator of the well are likely to be more reliable and correct.

Mandal, Saha and Kumar (2021) have equated their Jodhpur Formation with the Malani Igneous Suite and the Jodhpur Formation of Peters et al. (1995); the Bilara Formation/ Hanseran Evaporites with the Bilara, Hanseran Evaporite, Nagaur and Upper Carbonate formations; and the Nagaur Formation with Badhaura Formation and Bap Boulder Beds. The miscorrelation of stratigraphic units by Mandal, Saha and Kumar (2021) (Figs. 1 and 2c) vis-à-vis the stratigraphic units of Peters et al. (1995) (Fig. 2a) are summarized in Table 1.

Such a drastic conclusion of identifying rock units in Baghewala-1 and other wells by Mandal, Saha and Kumar (2021) that do not coincide with the stratigraphic units identified by Das Gupta and Bulgauda (1994) and Peters et al. (1995) need more evidence and further detailed studies because the interpretations and conclusions derived by the authors on the basis of incorrect data are also incorrect. Therefore, the formation tops given by Mandal, Saha and Kumar (2021), therefore, need to be reviewed by the authors as all their interpretation and conclusions, based on their identification of formation boundaries, are highly questionable.

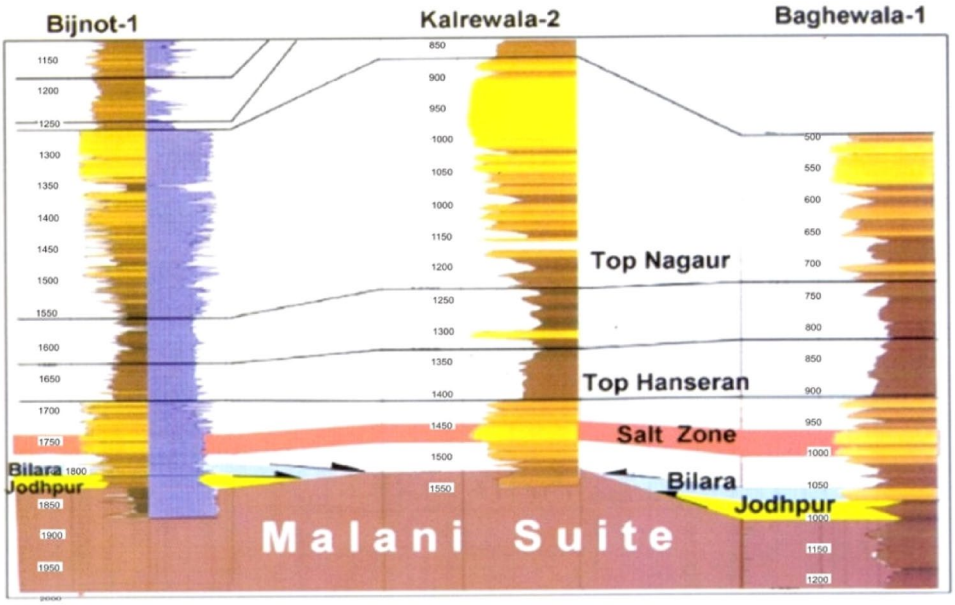

Fig. 3 Electric log correlation of Bijnot-1 well located in Punjab platform, Pakistan with Baghewala-1and Kalrewala-2 wells located in the Bikaner–Nagaur Basin, India (after Raza et al. 2008)

Table 1 Comparison of Neoproteozoic-Cambrian stratigraphic units in Baghewala-1 well identified by Das Gupta and Bulgauda (1994) and Peters et al. (1995) with the stratigraphic units identified by Mandal et al. (2021)

After Das Gupta and Bulgauda (1994) and Peters et al. (1995)		After Mandal et al. (2021)	
Badhaura Formation Bap Boulder Beds	Permian	Nagaur Formation	Cambrian
Upper Carbonate Formation Nagaur Formation	Cambrian	Hanseran Evaporite Bilara Formation	Neoproterozoic
Hanseran Evaporites Bilara Formation	Neoproterozoic		
Jodhpur Formation		Jodhpur Formation	
Malani Igneous Suite	Proterozoicc		
Basement	Precambrian	Basement	Precambrian

Responses as provided by the authors of the PEPT-D-20-00538 to the discussion

Understanding the geology of a basin is a dynamic process, and as the more data become available with time, the geological understanding of a particular region is updated. However, Mr. L.R. Chowdhary has initiated the discussion based on the analysis done by Das Gupta and Bulgauda (1994) and Peters et al. (1995) of well Bagewala-1 which was drilled in 1991 and is located in south western part of the basin. Mr. Chowdhary has attempted to re-enforce the understanding of above-mentioned workers mainly developed on the basis of this well only which was extended to Kalrewala-1 and Bijnot-1 (in Punjab platform). Mr. Chowdhary argues that stratigraphic boundaries of the formation tops should match with the lithology of the rock units and accordingly correlate with the log motifs of the well. This statement is not correct as the stratigraphic correlation across wells in a geologic setting is not always a lithology boundary.

Bikaner Nagaur basin is vast and it spreads across 77,000 Sq. Km in India and extends further in Pakistan. The basin has so far been explored by various operators through the drilling of multiple oil and gas exploration wells. Geological Survey of India has drilled at least 72 boreholes in the basin (Fig. 1) and these well data hold significant information on stratigraphy of the basin (Kumar et al. 2005). Mandal et. al. have considered GSI established stratigraphy (Fig. 2) for their study which is widely accepted by geoscientists who are working on various geological aspect of the basin, such as stratigraphy, age, correlation, depositional environment, palaeontological aspects, palaeomagnetism and basin configuration of Bikaner Nagaur Basin. Here, Mandal el. al has attempted to integrate data from various sources to build a more complete understanding on geological framework of the basin.

Mandal el. al. has integrated 16 profiles of 2D regional seismic reflection data acquired under NSP of total 2525 Line Kilo meter (LKM) along with well log, mud logs, core and biostratigraphy data of 9 oil & gas wells drilled by three different operators spread from north to south of the basin. Additionally, they have incorporated data /information of GSI drilled boreholes and geological studies carried out based on outcrop studies (Sharma et al. 2014; Paliwal. 2010a, b) in support of the developing the stratigraphic correlation of the basis.

In addition, following are some key aspects which contradict the argument by L.R. Chowdhary:

- Sulphur and strontium isotopic analysis (Mazumdar and Strauss 2006a, b) has been established that **Bilara carbonates and the Hanseran Evaporates Group (HEG) are time equivalent lateral facies variants**. The Bilara carbonates were deposited in the peripheral part of the basin (limited to the southern and eastern part of the basin) where as 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. Seven cycles of evaporite (H1–H7 halites) in Bilara/Hanseran evaporite group were reported based on the evidence from parametric wells drilled by Geological Survey of India (Kumar et al. 2005). Bromine analysis performed by GSI also proved the presence 7 halite cycles in the basin (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. Lower two cycles of evaporates, namely, H1 and H2 were regionally extensive and were identified in all the wells across the basin.

Both **Bilara carbonates and the Hanseran Evaporates Group (HEG)** overlie sediments of the Jodhpur Group and underlie sandstone and shales of the Nagaur Group. In these conditions, it makes no sense to state the Hanseran evaporites overlie the Bilara carbonates.

Nagaur group consists of Nagaur formation in the lower part and Tunklian Formation in the upper part in the basin (Stratigraphic chart established by Kumar et al. 2005, GSI).

- **Upper Carbonate (?):**

a. Limestone and dolomite sections of Upper Carbonate identified in Well Bagewala-1, has not been correlated to any other wells drilled in the adjoining areas. Moreover, outcrops located in the southwestern part of the basin (50 km from well Baghewala-1) did not exhibit evidence of upper carbonate (Sharma et al. 2014).
b. There is no evidence of Upper Carbonate formation above Nagaur Groups as per the core data of 72 wells drilled by GSI across the basin.
c. Dr. Paliwal also indicated that biostratigraphic data of Upper Carbonates corresponds to the time equivalent of

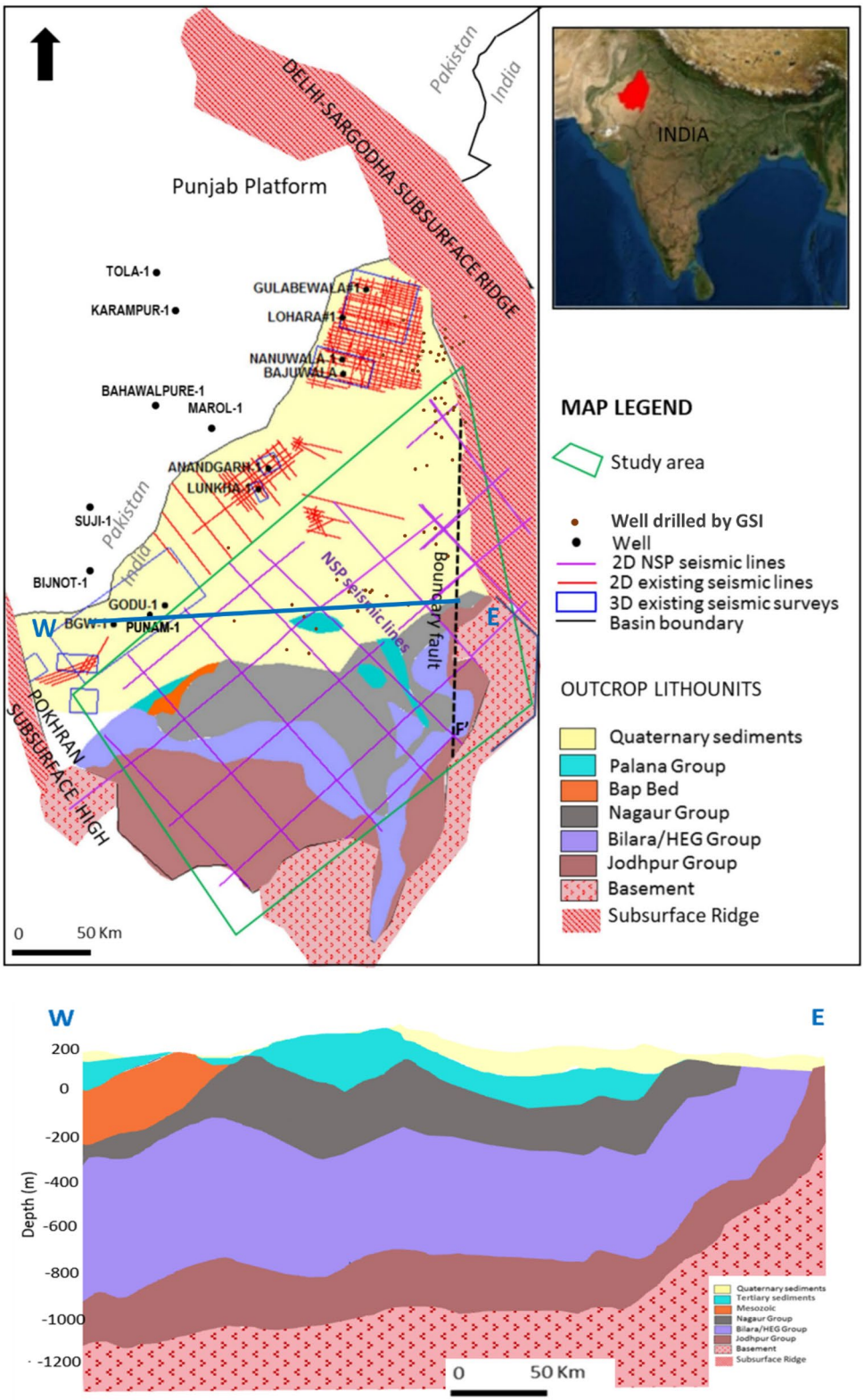

Fig. 1 Location map shows locations of wells drilled by GSI (in brown) and a geological section (W–E) across the BGW-1 and GSI wells (modified after Kumar et al. 2005) in the Bikaner–Nagaur basin

the Tunklian Formation of the Nagaur Group. (Paliwal 2010a, b)

Basement Mandal et al. has identified basement as the bottom of Jodhpur formation. There is no mention of identification of Malani Suite in the article. However, Mr. Chowdhary misinterpreted the study. Please see Table 1 below:

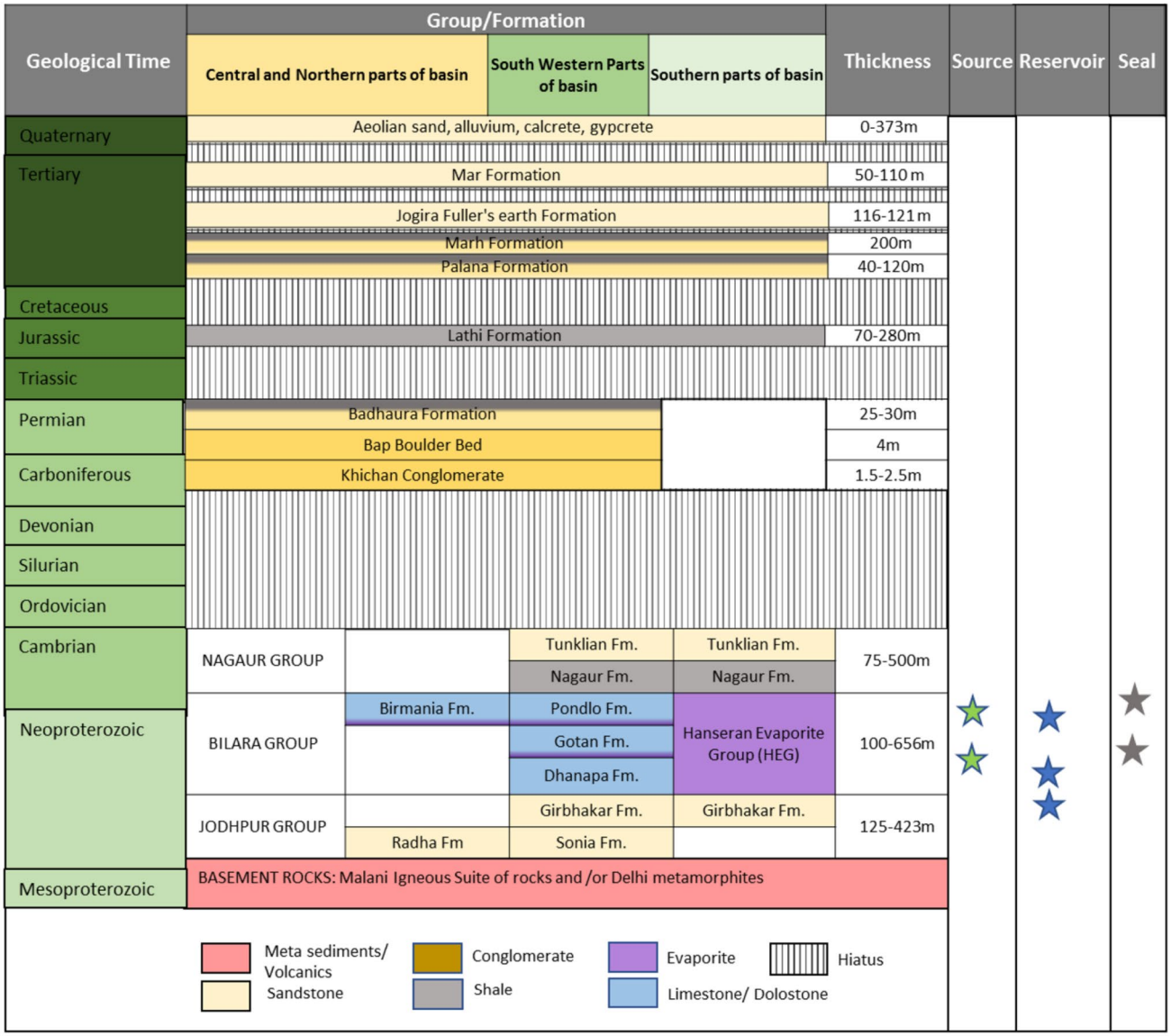

Fig. 2 Stratigraphy (Redrawn after Kumar et al. 2005) of Bikaner–Nagaur subbasin

Table 1 Comparison of stratigraphic units identified by Das Gupta and Bulgauda (1994) and Peters et al. (1995) with the stratigraphic units identified by Mandal et al. (2021)

Stratigraphic units (Formations)—Baghewala-1 well		
After Das Gupta and Bulgauda (1994) and Peters et al. (1995)	Age	After Mandal et al. (2021)
Badhaura Formation Bap Boulder Beds	Permian U Carboniferous	Badhaura Formation Bap Boulder Beds
Upper Carbonate Formation Nagaur Formation	Cambrian	Tunklian formation Nagaur Formation
Hanseran Evaporites Bilara Formation	Neoproterozoic	Bilara/ Hanseran Evaporites Group
Jodhpur Formation	Neoproterozoic	Jodhpur Formation
Malani Igneous Suite	Neoproterozoic	Basement
Basement	Precambrian	

In conclusion, it may be stated that that the stratigraphic units established by Mandal et al. is integrating all available data regionally spread across the basin in the most consistent and logical manner. In contrast, Mr. L R Chowdhary has based his arguments on a historical study done by earlier workers on a limited set of then available data. The earlier findings need to be updated in the light of recently acquired data which is the natural course of evolution and refinement of scientific analysis in any research area. This is unfair on Mr. Chowdhary part to term the study of Mandal et al. as questionable without putting sufficient effort to understand the context and value to significant amount and variety of data that has accumulated after 1995.

Addendum to Discussion "Structural Analysis and Seismic Stratigraphy for delineation of Neoproterozoic–Cambrian Petroleum Systems in Central and Eastern part of Bikaner–Nagaur Basin, India" by A. Mandal, D. Saha and A. Kumar, Journal of Petroleum Exploration and Petroleum Technology, vol. 12/6, June, 2021 (PEPT—D-20—00538)

Reply to Response by Mandal, Saha and Kumar to 'Discussion' by L.R. Chowdhary, 3451 Rockcliff Pl, Longwood FL 32779, USA. (lr.chowdhary@gmail.com).

Mandal, Saha and Kumar (2021) did not respond to the main issue in the 'Discussion' as to why they made such a drastic revision of the stratigraphic succession of Baghewala oil wells by Das Gupta and Bulgauda (1994), that these authors had developed based on lithological description of cuttings and cores of Baghewala-1, Tavriwala-1 and Kalrewala-2 wells by the Rajasthan Geological Group of Oil India ltd., and paleontological and palynological studies by P. Kumar of KDM Institute Exploration of ONGC. The author has been studying the geology and stratigraphy of the Bikaner–Nagaur Basin and the Punjab Platform for the last few years, limited to availability in public domain, and has a good understanding. Though, the Baghewala-1 well was drilled in 1991, the stratigraphy developed by these workers is reliable, as these authors were able to identify and describe the common rock types, such as sandstone, shale, marl, dolomitic limestone, anhydrite and salt, that constitute the stratigraphic column of Baghewala-1 well.

Based on his regional studies, the author has come to some primary conclusions and believes that these conclusions would help in better understanding the lithostratigraphy of the basin:

1. The floor of the depositional basin had highly uneven topography with a relief of a few meters to hundreds of meters in between the lows and highs. Due to the highly uneven topography, the Neoproterozoic sediments comprising the Sonia and Jodhpur formations were deposited filling the lows and after the lows were filled, the upper part of the sequence was deposited on the topographic highs, as in Baghewala-Punam high and probably also in Lunkha, Anandgarh, Bajuwala, Nanuwala, Lohara and Gulabewala highs. In some cases, where the topographic relief was a few hundred meters, as in Lal Suharna structure, drilled by Bahawalpur X-1 well in the Punjab Platform, an almost complete Neoproterozoic sequence was deposited in the topographic lows and the Cambrian Nagaur Formation was directly deposited over the basement in Lal Suharna topographic high (Ahmad et al. 2013), suggesting a relief of about 800 m.
2. After the deposition of the Cambrian sequence, the basin inverted and was exposed to erosion in two phases. During the first phase from Late Cambrian to Carboniferous, 'very little' erosion occurred basin wide, as a mildly positive area was formed followed by peneplanation to the base level that precluded further erosion. However, some evidence of erosion is seen in Suji-1, Marot-1, Bahawalpur X-1 and Baghewala-1 wells, evidenced by erosion of the Cambrian sequences in these wells (Das Gupta and Bulgauda 1994; Hasany et al. 2012; Asim et al. 2014).
3. During the Permian, the basin subsided towards the north and was uplifted towards the south and the uplifted part was exposed to erosion. During the deposition from Permian to Quaternary, there were several transgressive and regressive phases. Consequently, there was erosion ranging from a few meters to tens of meters, mainly in the southern part of the basin. This explains why the post-Nagaur sequence is absent in the eastern part of the basin, as it was mostly exposed to erosion from Permian to Upper Tertiary, whereas the post-Nagaur sequence was preserved in the Baghewala-Godu-Lohara-Gulabewala axis and towards the west of the Dulmera-Suratgarh basement high; this area also remained covered by Bap-Badhaura and Mesozoic formations.

Mandal, Saha and Kumar have made an interesting observation while arguing that the "stratigraphic correlation across wells in geologic settings is not always a lithologic boundary." In rock units, lithological character is the boundary of a formation. For example, the boundaries of the Bilara Formation are defined by unity of its lithologic character and when its lithologic character changes towards the north, the formation is not recognized as it becomes a part of the Salt Range Formation. According to the Code of Stratigraphic Nomenclature of India by Balasundaram et al. (1971), "The limits of the formation are those boundaries of lithologic change that give formation a greatest practical

unity of lithologic character." According to the North American Stratigraphic Code (1983), a formation is a body of rock identified by its lithic characteristics and stratigraphic position.

The author will now respond to Mandal, Saha and Kumar's response, which raised some key aspects contradicting the author's argument:

1. According to Mandal et al. (2021), it has been established that the Bilara carbonates and Hanseran Evaporites are time equivalent lateral facies variants, based on strontium and sulfur isotopic analysis by Mazumdar and Strauss (2006a, b). On the other hand, Banerjee et al. (2012) have argued that the Hanseran Evaporites is a successor unit of Bilara Formation and is therefore stratigraphically younger than the Bilara dolomites and has a distinct identity of its own.

The author, based on the following, argues that the Bilara Formation is stratigraphically younger than the Hanseran Evaporites:

- Absence of any inter-fingering between the Bilara carbonates and the Hanseran Evaporites;
- The wedging out of Bilara Formation to the east and wedging out of the Hanseran Evaporites to the west;
- The stratigraphic position of the Bilara Formation underlying the Hanseran Evaporites in the area of wedging out of the Bilara Formation, and
- A reduced depositional area upwards during the deposition of each salt cycle in Hanseran Evaporites with the lowest cycle occupying the largest area (Kumar and Chandra 2005).

Both the Bilara carbonates and the Hanseran evaporites overlie Jodhpur Formation and underlie Nagaur Formation but the Hanseran Evaporites also directly overlies the Bilara Formation in the wells located in the northwestern part of the basin, in Baghewala-Kalrewala, Punam, Marot and Bahawalpur E -1 wells.

When the lithologic character of a formation changes, it is given a new name. For example, the Neoproterozoic sequence comprising of Sonia, Jodhpur, Bilara and Hanseran formations in Baghewala -1 well due to lateral change in lithology is designated as the Salt Range Formation in Karampur, Sarai Sidhu, Marot, Fort Abbas and Darbula wells in the Punjab Platform.

2. The Nagaur Group consists of two formations, the lower Nagaur and the upper Tunklian formation in the outcrops. In the subsurface, however, the Tunklian Formation has not been recognized in any one of the wells drilled either in the Bikaner–Nagaur Basin or the Punjab Platform.
3. The Upper Carbonate Formation in the Baghewala-Kalrewala wells is a lateral equivalent of the Jutana Formation in the Punjab Platform wells and in the Salt Range province of Pakistan. The Upper Carbonate Formation is a subsurface unit, like the Hanseran Evaporites, and is not present in the outcrops. As explained above, the Upper Carbonates are absent in the southeastern wells (potash exploration wells) due to their non-deposition east of the Dulmera high or, if deposited, were removed during the second phase of erosion.

The author has given an alternate version of the log correlation, based on formation tops after Das Gupta and Bulgauda (1994) and Peters et al. (1995) (Figure 1). As the correlation is based only on the log motifs without the benefit of lithology of the rock units, it is tentative. According to this correlation, the Upper Carbonate Formation is present in Godu, Lunkha, Bajuwala and Nanuwala wells.

Paliwal (2010a, b) has suggested that "There is a faint possibility that the Upper carbonates corresponding to their Zone-VI are time equivalent of the Tunklian Formation of the Naguar Group" but did not recognize the Upper Carbonates as the Tunklian Formation. The Tunklian sandstone, at the surface, has its own lithologic identity distinctly different from the Upper Carbonate Formation.

4. Das Gupta and Bulgauda (1994) and Peters et al. (1995) have recognized Malani Igneous Suite (MIS) in Baghewala-1 well. According to Das Gupta and Bulgauda (1994, Table 1), it is composed of volcanoclastics with basalt and rhyolite lava flows. However, Mandal et al. (2021) included the MIS within their Jodhpur Formation and as such there is no mention of MIS in their article. They have given a table comparing the rock units recognized by Das Gupta and Bulgauda (1994) and Peters et al. (1995) with their rock units, which does not correspond with their log correlation given in their Figure 7. The author stands by the table given in his 'Discussion', prepared based on their log correlation.

In conclusion There are two versions of the formation tops—the first version given by Das Gupta and Bulgauda (1994) and Peters et al. (1995) and the second version by Mandal et al. (2021)—and only one version is correct. The author is of the opinion and the version by Das Gupta and Bulgauda (1994) and Peters et al. (1995) is correct because the rock units are defined by their lithologic character and the match between lithology and log motifs in the Baghewala well.

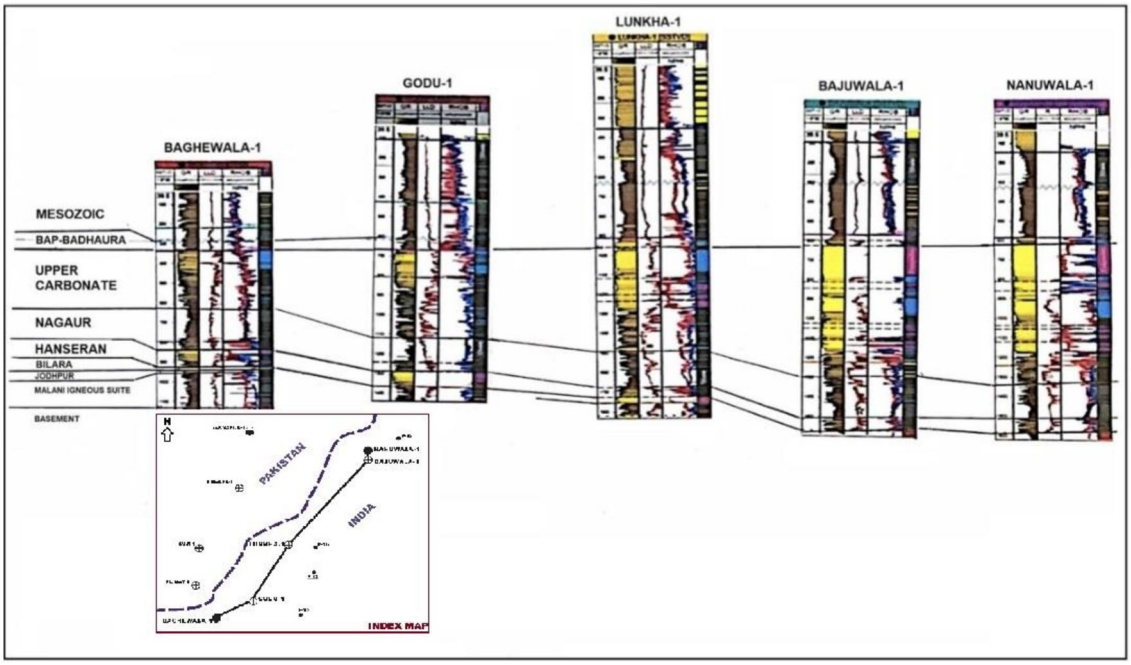

Fig. 1 Log correlation of Baghewala-1, Godu-1, Lunkha-1, Bajuwala-1 and Nanuwala-1 wells, based on the stratigraphic boundaries of Das Gupta and Bulgauda (1994) and Peters et al. (1995). (modified after Mandal et al. 2021) (logs, from left, are: SSTVD, GR, LLD (R in Nanuwala-1), RHOB/NPHI.)

Response to Chowdhary

Introduction

Mr. L. R. Chowdhary in his detailed note contends that the present authors have misidentified the six stratigraphic units, namely, Basement, Jodhpur, Bilara/Hanseran Evaporite (HEG), Nagaur and Mesozoic and Tertiary in the log signatures of 9 wells including Bagewala-1. His reference for this "misidentification" is based on the correlation represented in the paper of Das Gupta and Bulgauda (1994) which is different than the scheme followed by present authors. Das Gupta and Bulgauda (1994) in his paper have drawn a "tentative" correlation of Bagewala-1 (BGW-1) and Klrewala-2 (KLW-2). Later on, Peters et al. (1995) and Raza et al (2008) have referred to the same correlation of these wells as of Das Gupta and Bulgauda (1994). Although Das Gupta and Bulgauda themselves term these correlations as "tentative", Mr. L. R. Chowdhary considers these as more reliable and correct, citing the reasons that those authors had more information of core and log data to tie up formation tops. There is no such reference of this in the said paper.

Mandal et al. (2021) in their paper has attempted to develop a comprehensive understanding on the presence and distribution of the elements of petroleum system, structural configurations and stratigraphic features in central and eastern region of the Bikaner–Nagaur basin by integrating recent regional 2D seismic data (of 2018) along with earlier seismic and well data available in the basin which were acquired by multiple organizations, viz., GSI, ONGC, OIL, Essar oil, GSPC, etc., over a period of time.

Stratigraphic correlation of GSI

It may be recalled that in the year 2005, Geological Survey of India (GSI) carried out a detailed geological studies based on the core data of 72 wells drilled across the basin and established the stratigraphic framework (Kumar et al. 2005) of the basin which is well accepted by the geoscientific community (Sharma et al. 2014, Strauss et al. 2006, Kumar et al. 2008, Paliwal et al. 2009). Mandal et al. (2021) has considered the same stratigraphic scheme (Fig. 1.) that has been established by Geological Survey of India (GSI), to correlate six major stratigraphic boundaries, namely Basement, Jodhpur group, Bilara/Hanseran Evaporite Group (HEG), Nagaur Group, Mesozoic and Tertiary sedimentary packages across the basin. The present authors have attempted to correlate stratigraphic boundaries across wells; therefore, these boundaries may not always correspond to the same lithologic boundaries laterally.

Mr L. R. Chowdhary primarily emphasizes the correlation done by Dasgupta and Bulgauda (Das Gupta and

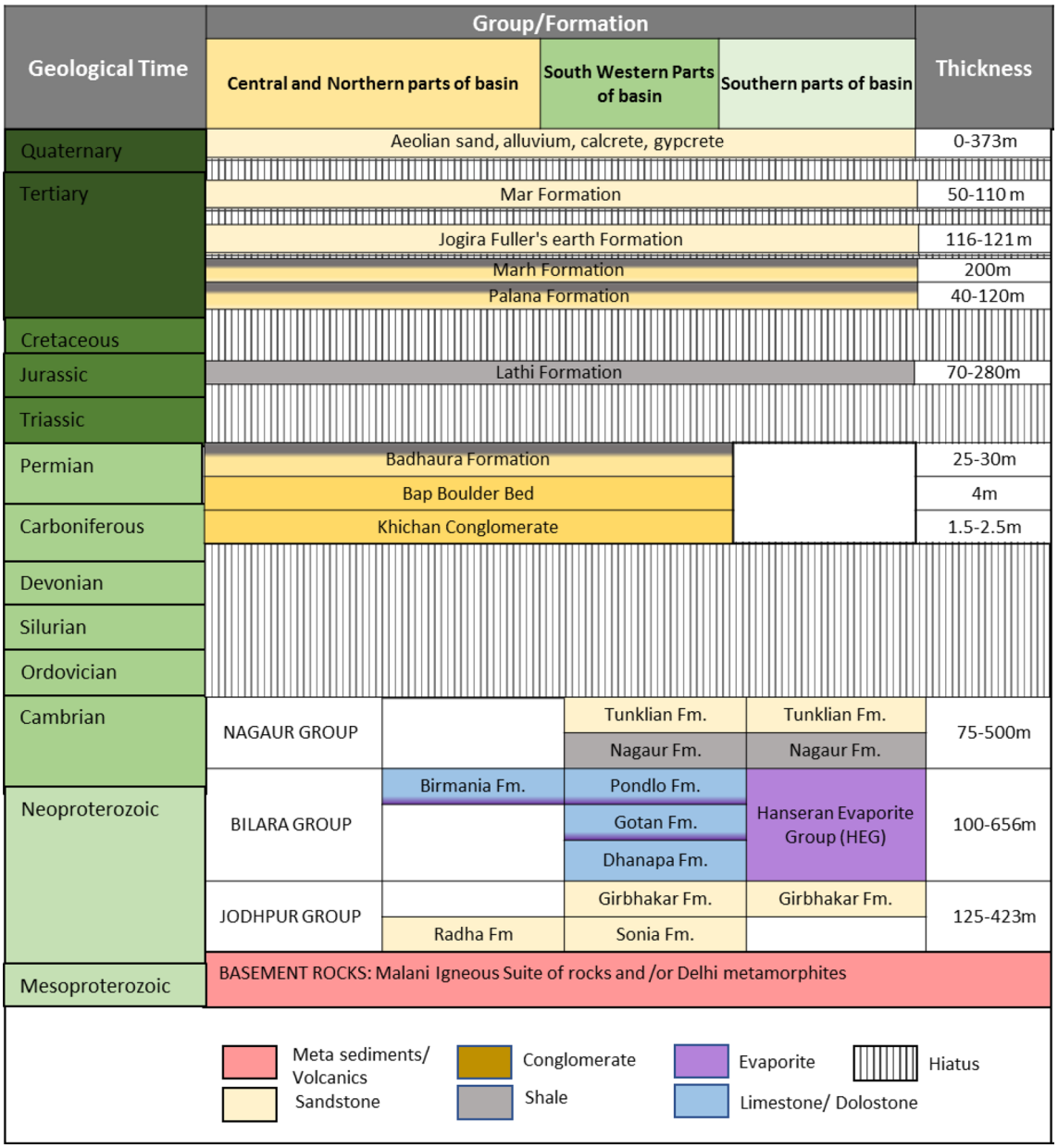

Fig. 1 Stratigraphy (Redrawn after Kumar et al. 2005) of Bikaner–Nagaur subbasin

Bulgauda 1994) based on the two wells Bagewala-1 and Kalrewala-2 which are located just south western corner of the basin (Baghewala block, Fig. 2). Present authors observed inconsistency between the stratigraphy framework established by Kumar et al. 2005 (GSI) and Das Gupta and Bulgauda 1994.

Discussions

The present authors intend to respond to the concerns and issues raised Mr L. R. Chowdhary in a systematic manner in the following way:

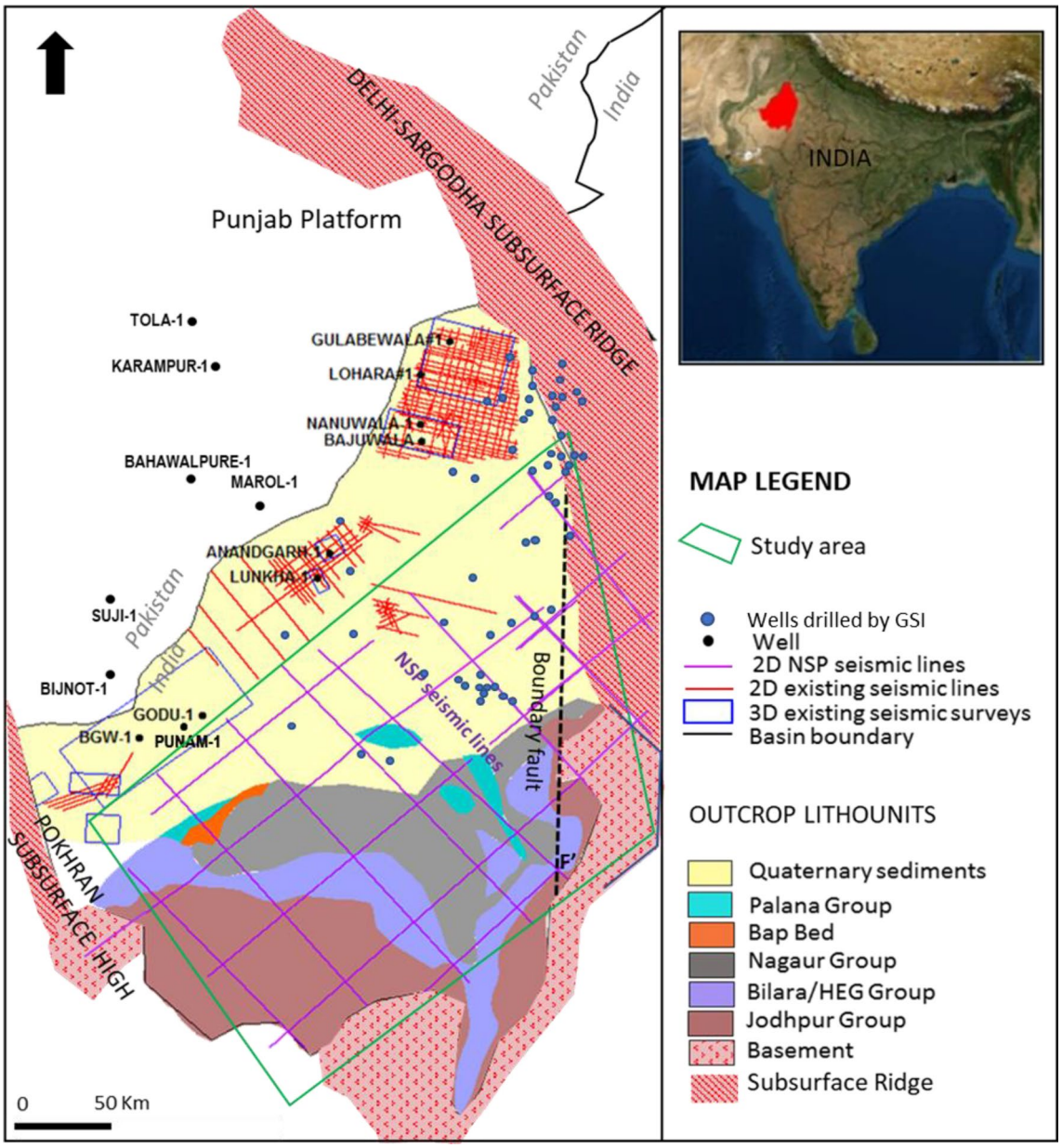

Fig. 2 Stratigraphic framework established by Kumar et al. 2005 considered outcrop data and 72 well data marked by blue color (drilled by GSI) whereas stratigraphic framework established by Das Gupta and Bulgauda's (1994) considered well data of BGW-1 and Kalrewala-1, which are geographically restricted to south western corner of the basin

Why did the present authors not use Bulgauda and Das Gupta's (1994) stratigraphic framework to correlate wells across the basin?

- **Bilara and Hanseran Evaporates Group (HEG) are time equivalent**

Mr L.R. Chowdhary argues that the Hanseran Evaporite Formation is stratigraphically younger than the Bilara Formation and correlated the same in the Baghewala-1 (BGW-1 well). However, Mazumdar and Strauss (In 2006) established that Bilara carbonates and the Hanseran Evaporates Group (HEG) as time equivalent lateral facies variants based on the sulphur and strontium isotopic analysis. Samples from outcrop near Bilara, Dhanapa, Ransigaon and Ghagrana (GAG) villages and cores of GSI wells P-47 and P-12 and P-4 were studied by Strauss et al. 2006 for sulfur- Strontium isotopic analysis. Mazumdar and Strauss (2006a, b) further suggested an asymmetric depositional pattern for the carbonate, sulphate and halite (Fig. 3b). The Bilara carbonates which mostly found in

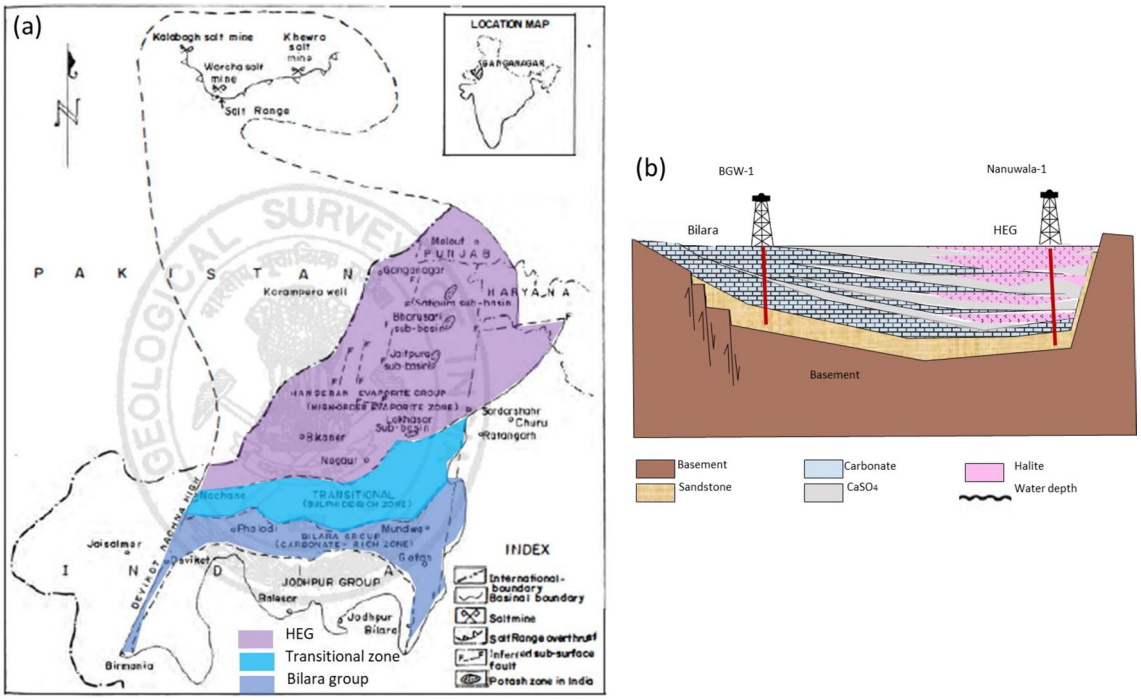

Fig. 3 **a** Map showing lateral lithofacies variation from Bilara limestone to sulphate-predominating facies to HEG halites (Redrawn after Kumar et al. 2005). **b** South to North schematic cross section depicts depositional environment and basin configuration during deposition of Bilara carbonate/age equivalence HEG halite. 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

the southern and eastern part of the basin, were deposited in the peripheral part of the basin, whereas 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 basin depocentre (central and northern part of the basin). Figure 3a depicts the map that shows lateral lithofacies variation from Bilara limestone to sulphate-predominating facies to HEG halites (Redrawn after Kumar et al. 2005). Geological Survey of India (Kumar et al.2005) conducted geochemical analysis (concentration of bromine) of the halites layers intersected by 72 wells to evaluate the evaporation history of the basin and established presence seven cycles of evaporite (H1–H7 halites) in Bilara/Hanseran evaporite group. 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. Lower two cycles of evaporates, namely, H1 and H2 were regionally extensive and were identified in all the wells across the basin including Baghewala (BGW-1) and Godu-1. BGW-1 intersected H1 and H2 halites at 837 m and 794 m tvdss, respectively. Therefore, Mr. L. R. Chawdhary's claim that there is no interfingering between the Bilara carbonates and the Hanseran Evaporites is not correct.

- **Upper Carbonate Formation of Das Gupta and Bulgauda is part of Bilara and HEG Group**

According to Das Gupta and Bulgauda (1994), the shallower Limestone and dolomite units were identified in well Bagewala-1, characterized as Upper Carbonate formation. Mr. L. R Chowdhary further correlated the Upper Carbonate formation with Godu, Lunkha, Bajuwala and Nanuwala wells. However, the stratigraphic correlation proposed by Mr. L. R Chowdhary contradicts with the correlation established by Geological Survey of India (Fig. 4 and 5) and Mandal et al. 2021. It is suggested that Mr. L. R Chowdhary may consider the following points for considering Upper Carbonate Formation of Das Gupta and Bulgauda as part of Bilara and HEG Group in our scheme of correlation. First, the core data of the 72 wells drilled by GSI across the basin (Fig. 2) did not identify the so-called Upper Carbonate formation above the Nagaur Group. GSI wells-19, 42 are located approximately 10–15 km from the well Nanuwala-1 and Bajuwala, however, no Upper Carbonate Formation was reported here also by GSI. In addition, GSI well- 16 which is located just adjacent to Lunkha-1 did not exhibit any existence of Upper Carbonate formation. Finally, the outcrop exposures located in the south-eastern part of the basin (~ 50 km from well Baghewala-1) did not exhibit Upper Carbonate (Sharma et al. 2014).

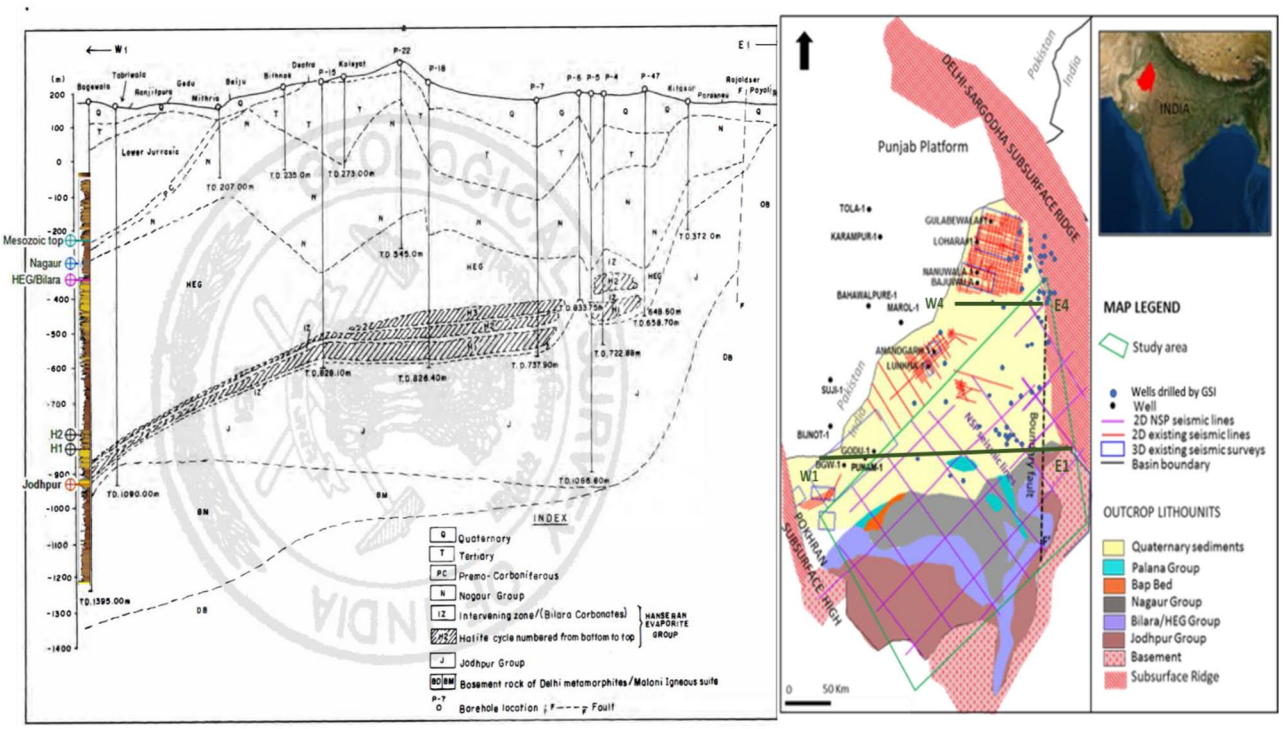

Fig. 4 Geological cross section along W1–E1 line (modified after Kumar et al. 2005), where stratigraphic units identified in well BGW-1 are correlated with GSI drilled wells

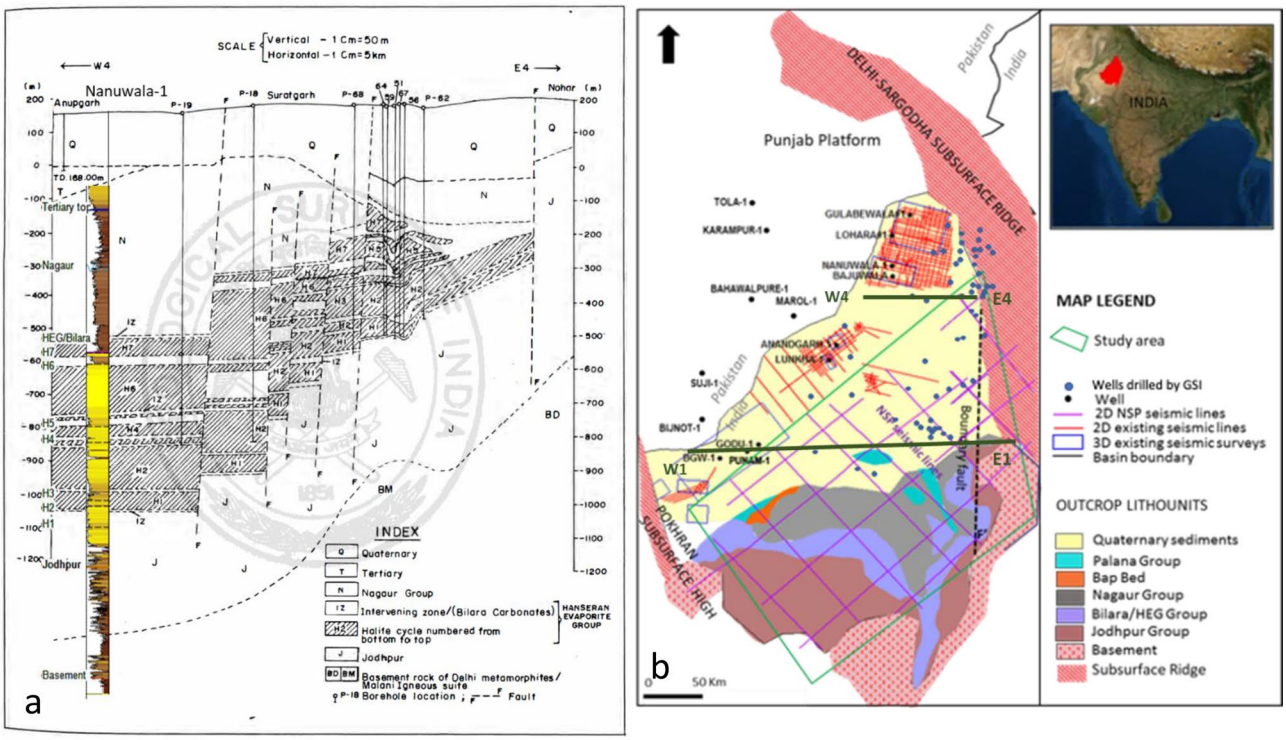

Fig. 5 **a** Geological cross section along W4–E4 line (modified after Kumar et al. 2005), where stratigraphic units identified in well Nanuwala-1 (Projected) are correlated with GSI drilled wells **b** showing the base map

Clastic dominated (sandstone and shales) of the Nagaur Group overlie both Bilara carbonates and the Hanseran Evaporates Group (HEG). Nagaur Group comprises of Nagaur Formation and Tunklian Formation, which is why it has been termed as a "Group" in the stratigraphic chart shown in Fig. 1. Base of the Nagaur group exhibits gradational contact with underlying Bilara/HEG group. The upper part of Nagaur group primarily is composed of siltstone with thin, fining upward sandstone layer and is interpreted to have been deposited in continental fluvial environment. Therefore, shallowest carbonate identified in the wells have been correlated as top of the Bilara/HEG group and underlying Nagaur Group.. Regional geological cross-sections combining Oil wells and GSI drilled parametric wells have been shown in Figs. 4 and 5 from where it is evident that well correlation by Mandal el. al. (2021) matches with GSI well markers.

References

Ahmad A, Farooq U, Javed T, Ali M (2013) Exploring the Infra-Cambrian petroleum system in Punjab platform: lessons from Bahawalpur X-1 well: datapages/search and discovery article #9020802013, PAPG/SPE Annual Technical Conference, 26–27 Nov 2013, Islamabad, Pakistan (abstract)

Balasundaram MS et al. (1971) Code of Stratigraphic Nomenclature of India: Geological Survey of India, Misc. publication no. 30, p 1-18

Banerjee DM, Rastogi SP, Kumar V (2012) Some evaporite deposits of India: proc. Indian national science academy, vol 78/3, pp 401–406

Das Gupta U, Bulgauda SS (1994) An overview of the geology and hydrocarbon occurrences in the western part of Bikaner-Nagaur Basin. Indian J Pet Geol 3(1):1–17

Hasany, TS, Aftab M, Siddiqui A (2012) Refound exploration opportunities in Infra-Cambrian and Cambrian sediments of Punjab Platform, Pakistan: Science and Discovery article # 50576

Kumar V, Chandra R (2005a) Geology and evolution of Nagaur-Ganganagar basin with special reference to salt and potash mineralization. Geol Surv India 62:151

Mandal A, Saha D, Kumar A (2021) Structural analysis and seismic stratigraphy for delineation of Neoproterozoic-Cambrian petroleum systems in central and eastern part of Bikaner-Nagaur Basin, India. J Explor Pet Technol. https://doi.org/10.1007/s13202-0210-01432-7

Mazumdar A, Strauss H (2006b) Sulfur and Strontium Isotopic Composition of the carbonates and evaporate rocks of Neoproterozoic-Early Cambrian Bilara Group (Nagaur-Ganganagar Basin, India): constraints on Intrabasinal correlation and Global Sulfur Cycle: in Geology and Hydrocarbon Potential of Neoproterozoic-Cambrian basins of Asia, edited by Bhat et al., Geological Society of London, spl. pub. 366.

Mazumdar A, Strauss H (2006a) Sulfur and strontium isotopic compositions of carbonate and evaporite rocks from the late Neoproterozoic–early Cambrian Bilara Group (Nagaur–Ganganagar Basin, India): constraints on intrabasinal correlation and global sulphur cycle. Precambrian Res 149:217–230

North American Commission on Stratigraphic Nomenclature (NACSN) (1983) North American stratigraphic guide. AAPG Bull 57(5):841–875

Paliwal BS (2010a) Discussion: a review of the Stratigraphy of Marwar Supergroup of West-central Rajasthan. PANDEY, D.K. and BAHADUR, T. (2009). J Geol Soc India 75:415–431

Paliwal BS (2010b) Discussion 'Late Neoproterozoic (Ediacaran) – Early Paleozoic (Cambrian) Acritarchs from the Marwar Supergroup, Bikaner-Nagaur Basin, Rajasthan' by Biju Prasad, Ram Asher and Bihuti Borgohai. J Geol Soc India 75(2010):415–431

Peters KE, Clark ME, Das Gupta U, McCaffrey MA, Lee CY (1995a) Recognition of an Infracambrian Source Rock based on Biomarker in the Baghewala-1 oil, India. AAPG Bull 79:1481–1494

Raza HA, Wasim A, Ali MS, Mujtaba M, Alam S, Shafiq M, Iqbal M, Noor I, Riaz N (2008) Hydrocarbon prospects of Punjab platform Pakistan, with special reference to Bikaner-Naguar Basin of India. Pak J Hydrocarb Res 18:1–33

Sharma M, Pandey SK, Kumar S (2014) International field workshop on the Marwar Supergroup, Rajasthan, Western India, pp 1–88