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ORIGINAL PAPER

Types and nature of fracture associated with Late Ordovician paleochannels of glaciofluvial Sarah Formation, Qasim region, Central Saudi Arabia

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Abstract This study evaluates the Late Ordovician glaciofluvial deposits of the Sarah Formation and equivalent outcroppings in north, central, and southwestern Saudi Arabia. The Sarah Formation also covers a wide area in the subsurface and is considered as an important target for unconventional tight gas reservoir. Defining the fracture types, nature, and distribution in outcrop scale might help to establish a successful fracture simulation model and behavior for the Sarah tight gas reservoir in the subsurface. This study investigates fracture characteristics for the Sarah Formation at Sarah paleochannel outcrops. The study revealed three sets of fractures, which have EW, NS, and SE-NW directions, and these fractures vary from open, resistive, and filled to resistive fractures. The closed fractures are filled with ferruginated iron oxides and gypsum. The filled fractures (the thrust boundary) are found in the study area at the SE-NW strike fracture set, while open and resistive fractures are found mainly at S-N and E-W fracture sets, respectively. The syn-depositional filled fractures (iron oxides) are considered as the younger fracture sets while the open and resistive fractures are post-depositional fractures which may have resulted from uplift or tectonic movement. A general model representing the fracture pattern and the thrusting boundaries due to glacial movement was constructed. It has been noticed that the systematic occurrence of filled fractures (thrust boundaries) described the boundaries between different glacial events, which act as a fluid barrier (filled fractures) and decrease the reservoir quality. The finding of this study might be utilized as a guide and lead for exploration in the subsurface Sarah glacial deposits. It will also help to understand and speculate the nature pattern and distribution of fractures with the Sarah Formation.

Keywords Sarah formation · Fracture types · Glaciofluvial deposits · Tight reservoir · Fracture model

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Introduction

The Late Ordovician glaciofluvial deposits of the Sarah Formation were distributed along central and NW Saudi Arabia (Vaslet 1989; McGillivray and Husseini 1992; Clark-Lowes 2005) as a first glaciofluvial event in the Arabian Peninsula. The deposition of Late Ordovician sediments corresponding to the Ordovician-Cambrian first-order retrogradational sequence set is characterized by 200-m-thick glacial sediments, extending from Oman to Spain and from Mauritania to Saudi Arabia (Ghienne 2011). The Sarah Formation was cropped out in central and NW Saudi Arabia as an incised paleovalley and covers wide areas in the subsurface.

Regionally, Saudi Arabia is considered as a part of the North Gondwana platform with Libya, Mauritania, Niger, and Algeria. Most of the Middle East and North Africa were subjected to Hirnantian glaciation (Le Heron et al. 2009). The North Gondwana platform is considered the proximal ice zone, and most of the glaciation features can be found throughout the internal platform. The distal part of the ice zone includes Spain, Morocco, and Turkey (Ghienne 2011).

The Sarah Formation and its equivalents are found exposed in central and northwestern Saudi Arabia, including glacial and pre-glacial sediments considered as a paleovalley infill of the Late Ordovician age. The Arabian plate underwent two glacial events in two different geologic ages. The global Late Ordovician glaciation is well known and documented in the Arabian Peninsula and results in the formation of Sarah and Zarqa formations which form paleovalleys incised deeply into the lower formations (Qasim and Saq formations and the basement) as studied by Vaslet et al. (1994), Bartlett et al. (1986), Janjou et al. (1996a, b), Vaslet et al. (1986), Williams et al. (1987), and Manivit et al. (1987). The thickness of the Sarah Formation in the center of the Arabian Plate varies from a hundred to several hundred meters of fine- to medium-grained sandstones with tillite facies of glacial to marine origin (Senalp and Al-Laboun 2000). The Paleozoic glacial and fluvial strata are found to be well exposed in central Saudi Arabia; equivalent glacial deposits are also recorded at the Wajid Formation in southwestern Saudi Arabia and northern Saudi Arabia, and there is limited subsurface occurrence in the Rub Al-Khali Basin (Stump and van der Eem 1995; Moscariello et al. 2009).

The glaciotectonic deformation in glacial systems took place when the stress of insurgent glacial input exceeds the strength of the material infront or beneath it. Many glaciotectonic features are found in the Sarah paleovalley such as thrust boundaries, tectonic lamination, folding, and fractures in different scales. The glaciotectonic deformation can be brittle (thrust, faults) or ductile (fold) (Bennett and Glasser 2011). The factors controlling the ductility or brittleness behavior of the glacial sediment deformation is the pore-water pressure. The brittle deformation in glacial deposits occurs in low pore-water pressure within the sediment, while in high pore-water pressure the glaciers were deformed in a ductile manner (Van der Wateren 1995). The tectonic feature characteristics in the Sarah paleovalley can be compared to many glaciogenic systems. Similar glaciotectonic features in the Sarah paleovalley (thrust, fractures, and folding) are found in many current glacial systems such as Mons Klint in Denmark, the Vatnajokull ice cap in Iceland, and the Uversbreen push moraine in Svalbard. The glacial sediment surge input to the glacial system is the main factor controlling the deformational features in different glacial sediments.

Geological setting

The Sarah Formation is exposed in more than six paleovalleys, which are deeply incised into the Saq Sandstone, Zarqa Formation, and Qasim Formation at the Baqa area (Fig. 1a, b). The Sarah Formation is considered as a tight gas sandstone reservoir with mostly unexplored areas

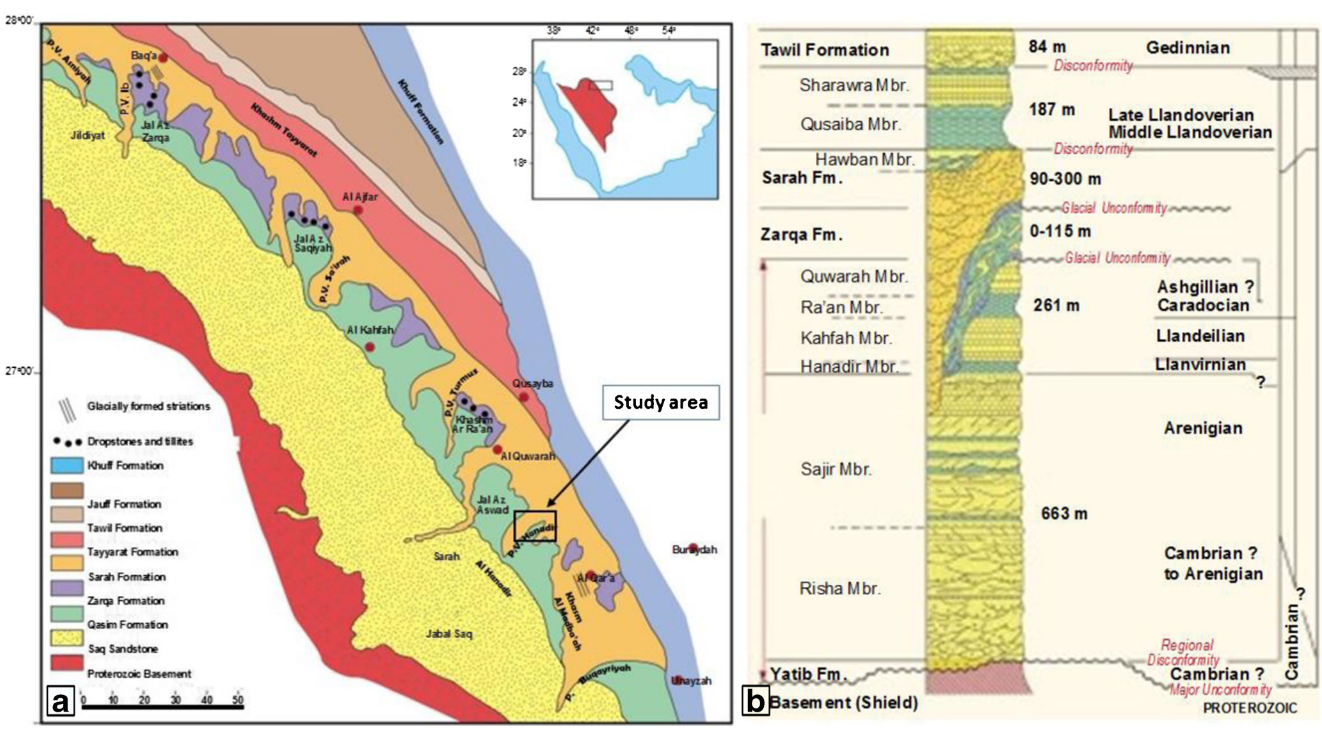

Fig. 1 **a** Paleovalley distribution in the Al-Qasim area, Saudi Arabia. **b** The paleozoic stratigraphy of Central Saudi Arabia including the glacial Sarah Formation (Senalp and Al-Laboun 2000) and the Rawd Al-Jawa paleovalley

Fig. 2 Photograph for the location of the study area (Sarah paleovalley)

of the paleozoic petroleum system (Millson et al. 1996; Schenk and Pllastro 2000). Regionally, equivalent glacial deposits are recorded in southern Turkey, Algeria, and Mauritania (Moscariello et al. 2009). The Sarah Formation is considered one of the important targets for unconventional natural gas resources in Saudi Arabia. The fracture characteristics of the Sarah Formation were studied by Bukhamseen et al. (2010) in the subsurface at the Rub

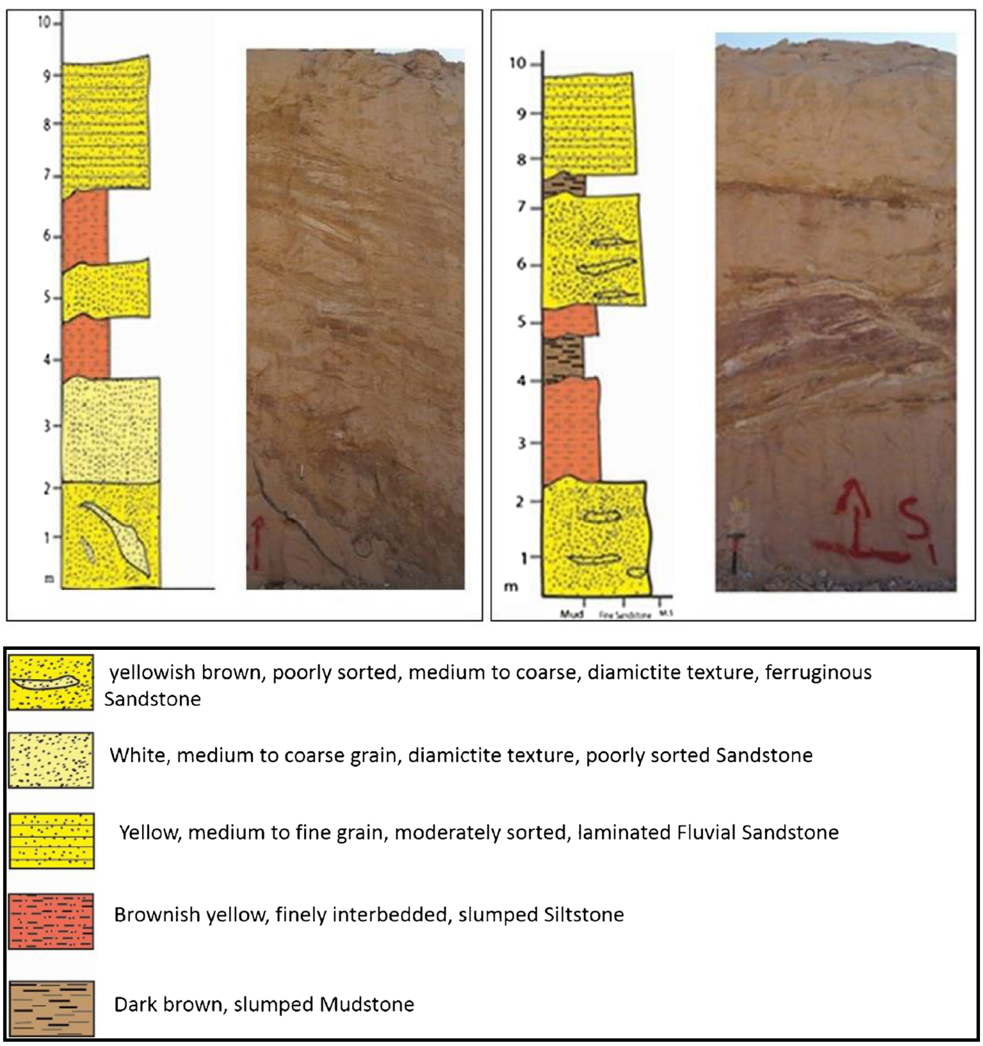

Fig. 3 Vertical stratigraphic section for location 1 and location 2 at the Sarah paleovalley

Al-Khali Empty Quarter of Saudi Arabia. They described three types of fracture fill ranging between resistive, closed fracture to conductive, and open fractures. The conductivity of fractures and fracture fill was described by Bukhamseen et al. (2010) without explanation to the type of fracture fill. This study might lead to understanding the obstacles in the subsurface for the Sarah Formation reservoir.

Rawd Al-Jawa paleovalley

The Rawd Al-Jawa glaciofluvial paleovalley is located at Rawd Al-Jawa town, 30 km west to Buraydah town, Qasim region. Like other paleovalleys, the Rawd Al-Jawa Paleovalley is oriented to northeast direction. The study area (Fig. 2) is located along the road cuts striking east-west and north-south directions. The length of the road cut is about

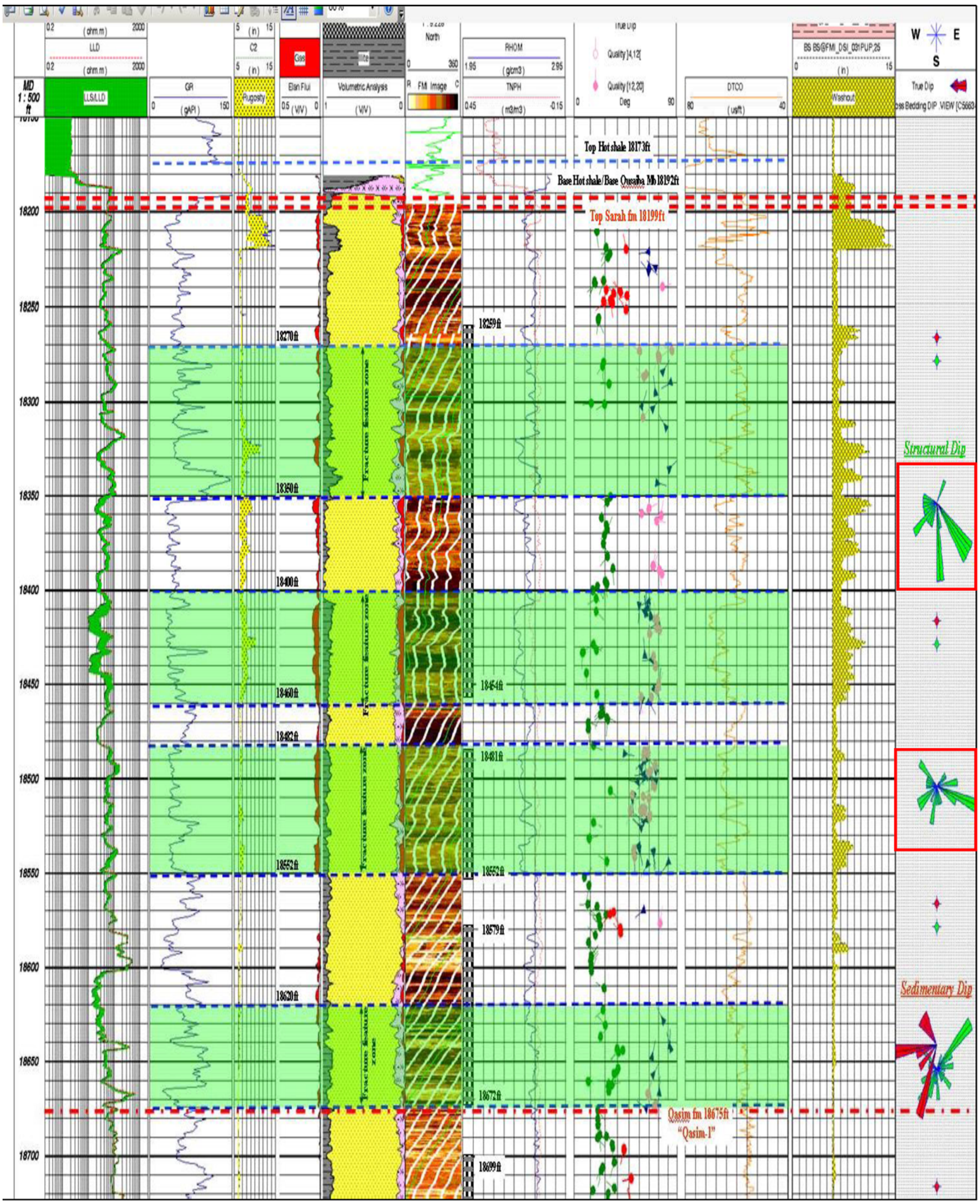

Fig. 4 Fracture zones and orientations for the Sarah reservoir in the subsurface at the Rub Al-Khali Empty Quarter of Saudi Arabia (Bukhamseen et al. 2010)

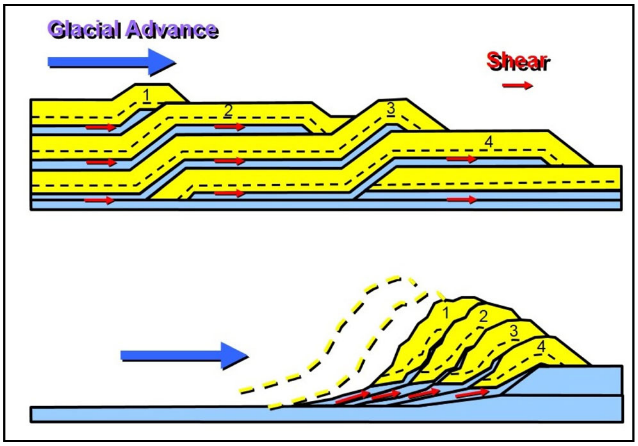

Fig. 5 Glaciotectonic stack model for glacial push moraines at the Unayzah Formation (Melvin and Norton 2013)

500 m and the width of the road cut is about 250 m. The vertical stratigraphic section is selected at locations N 26 33.708, E 43 35.758 (section 1) and N 26 33.706, E 43 35.768 (section 2) along the south wall of the outcrop (Fig. 3). The general morphology of the outcrop reflects clear glacial environment with a large boulder of diamictite texture. In addition, the slumped mudstone reflects the glaciotectonics along the paleovalley.

Stratigraphic section

Detailed stratigraphical studies were conducted along selected vertical sections to create the vertical stratigraphic sections, which help to study and describe the vertical lithofacies changes. Figure 3 describes the vertical stratigraphic sections for location 1 (N 26 33.708, E 43 35.758) and location 2 (N 26 33.706, E 43 35.768). The main lithologic feature for the studied paleovalley on outcrop scale is the presence of large boulders of diamictite transformed by glacial movement along the paleovalley. The large boulders of diamictite indicate short distance of transformation and closer distance from the source of glaciation movement to the area of deposition, as described by Ghienne (2011). This was confirmed on meso scale and thin section scale by the presence of poorly sorted diamictites with angular edges indicating source rock.

Fracture characteristics

The fractures in the study area are characterized using a scan line method (number of fractures per unit area), field measurements, and laboratory analysis (SEM-EDS, XRD, and thin sections). The fractures in the outcrop are mostly oriented in NW, SE, or EW directions. The fracture description for the Sarah Formation had not been studied on outcrop scale. The Sarah Formation fractures had been studied by Bukhamseen et al. (2010) who established a subsurface fracture simulation model for the Sarah tight gas reservoir in the Rub Al-Khali Empty Quarter of Saudi Arabia. The fractures in the study area describe one set of the fractures sheared and that followed the direction of the glacial flow to form discontinuity surfaces separating different sandstone packages. The subsurface fracture data derived by Bukhamseen et al. (2010) (Fig. 4) are well correlated with those found at the studied outcrop. The studed fractures at outcrop scale might help to understand and predict the fracture characterstics in the subsurface.

Melvin and Norton (2013) proposed a model for the glaciation mechanism in the Unayzah Formation (Fig. 5). The model defines thrusting boundaries and shear zones resulting from the glacial movement. The shear zones and thrusting boundaries found in the studied area are associated with horizontal to subhorizontal features along the direction of

Fig. 6 Sarah paleovalley stack pattern and thrust boundaries

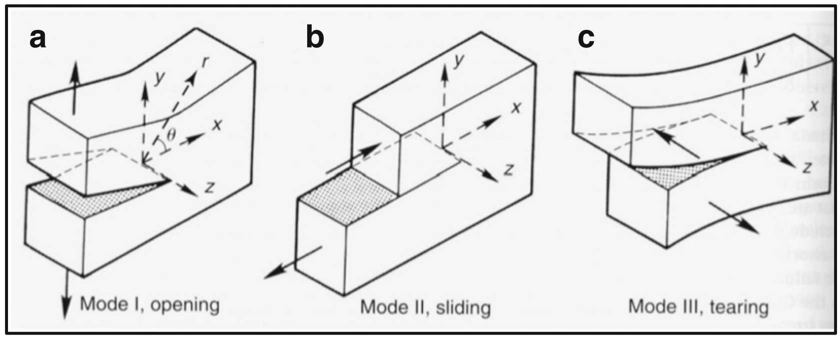

Fig. 7 Fracture mode types. **a** Mode I (opening mode). **b** Mode I (sliding mode). **c** Mode III (tearing mode) (Kanninen and Popelar 1985)

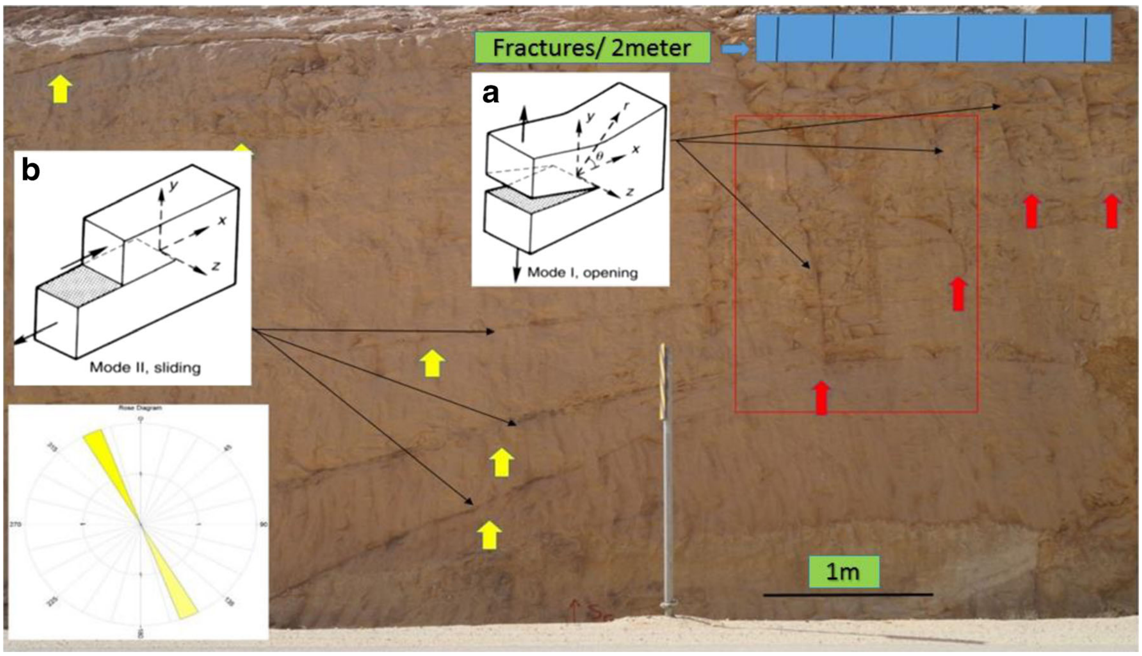

Fig. 8 Thrust fracture and open fracture relationships with fracture intensity and modes in the Sarah paleochannel

the glacial flow. The sheared and thrusting boundaries represent the unconformity boundary separating different glacial periods. The thrusting boundaries are characterized by the presence of ionization and ferruginous sandstone with

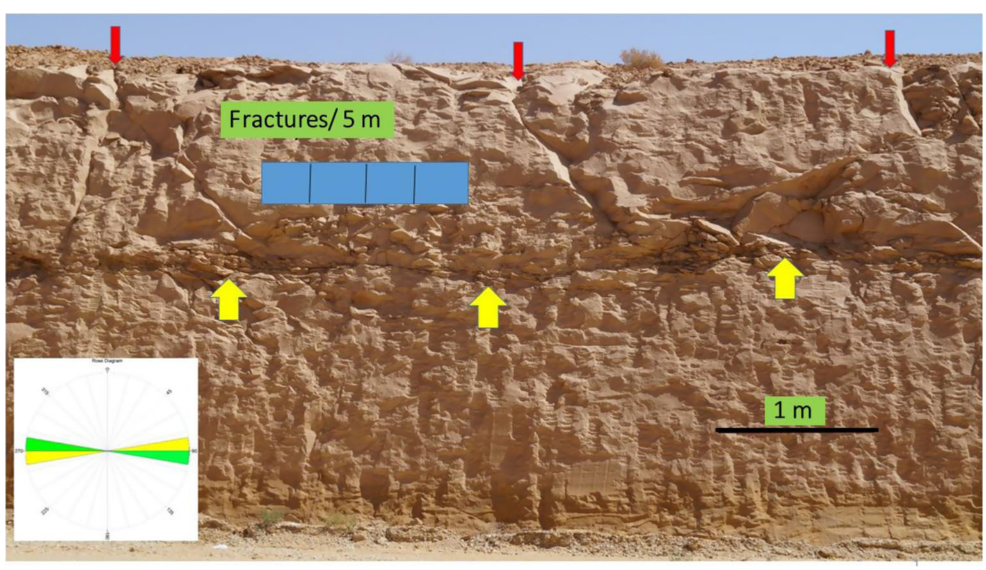

Fig. 9 Shear fracture set (mode III fracture set) E-W strike fracture sets at the Sarah paleochannel

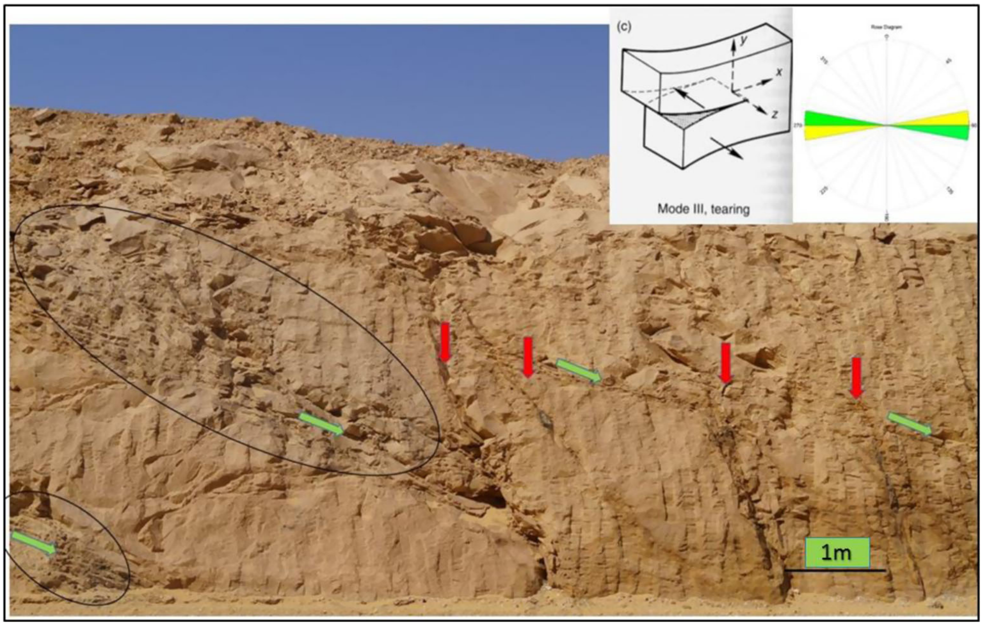

Fig. 10 E-W strike fracture propagation in different lithologic units at the Sarah paleochannel

negligible porosity values, which act as a fluid barrier preventing the fluid to move between different lithological units. The studied outcrops have the same characteristics of the Melvin and Norton (2013) model as shown in Fig. 6.

Fracture modes

The deformation modes of the fracture were proposed by Kanninen and Popelar (1985). The mode I fracture takes place when the rock units move away from each other and perpendicular to the fracture plane (Fig. 7a). Mode II takes place when the rock units move past each other and parallel to the fracture planes (Fig. 7b). Mode III occurs when the rock units move with angle to each other and cased by the shear displacement (Fig. 7c). Each type of fracture mode has specific characteristics to the reservoir quality. The mode I fracture type represents the best type for reservoir quality which results in an open fracture type while mode II and mode III result in closed to resistive fractures.

Figure 8 describes mode I, the opening mode fracture, while mode II is the sliding mode fracture. The open fractures cut the thrust fractures and are considered younger in age than the thrust fractures. The opening fractures increase the

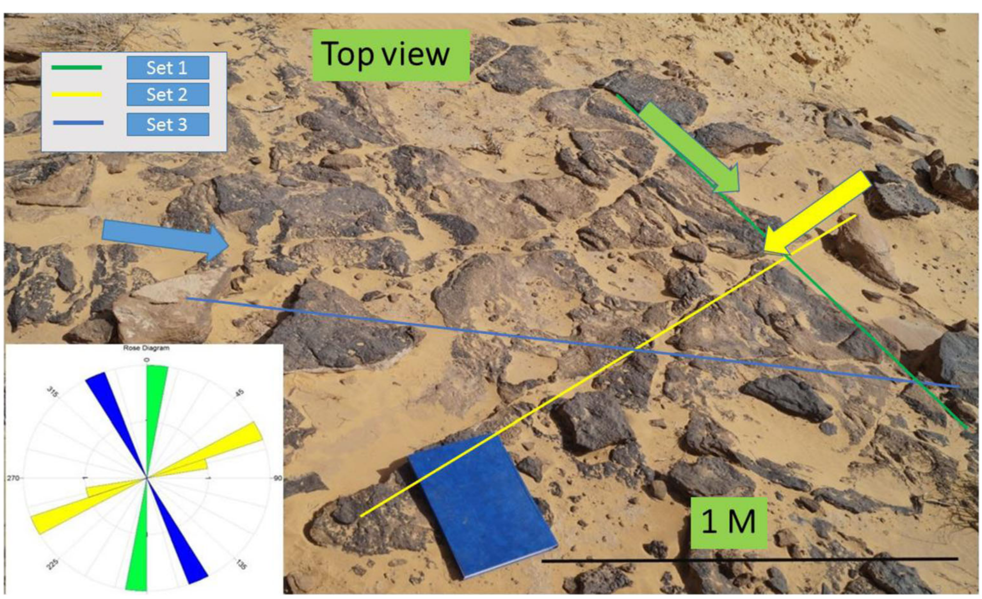

Fig. 11 *Top view* for the three sets of fractures indicated by *colored lines* at the Sarah paleochannel fracture fill and fluid barrier

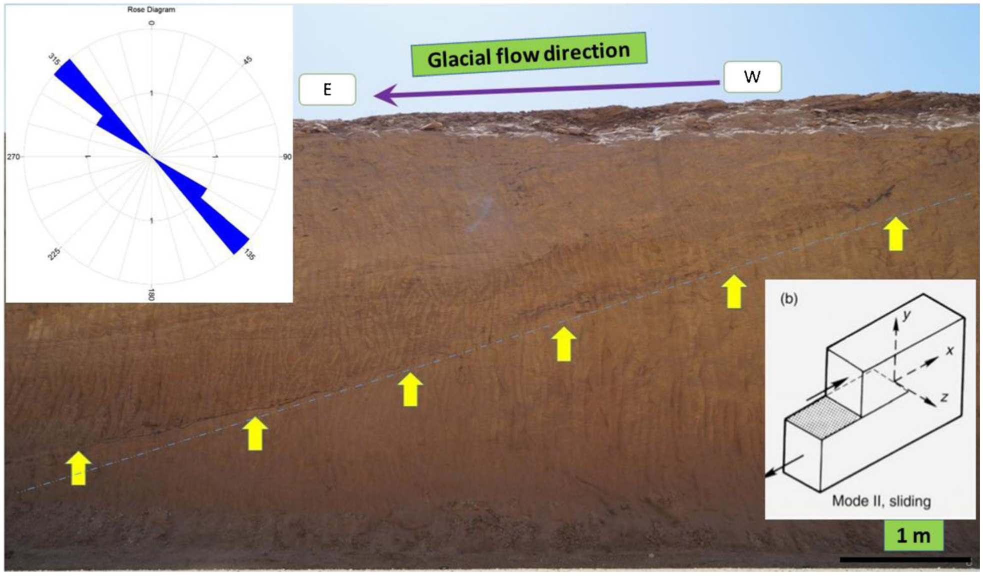

Fig. 12 Photograph describing the glacial flow direction and the thrust boundary which represent fracture slide mode (mode II)

reservoir quality while the thrusting fractures act as a barrier for fluid movement and decrease the reservoir quality. The three types of fracture modes are detected at the Sarah paleochannel at three sets of fractures oriented in E-W, N-S, and NW-SE directions.

The E-W fracture sets showed preferred propagation to the lithologic composition, which act as units having different fracture properties confined with the lithologic change of rock units (Fig. 9). The shearing fracture mode (mode III), also found at the eastern wall of the paleovalley, describes the shear mechanism of fracturing. The sheared fractures are also syn-depositional fractures ranging between closed to resistive fractures having an E-W strike direction. The shearing fractures are common in the glacial environment because of their glacial deposition mechanism. The scales of sheared fractures are of sub-seismic scale, and it is very difficult to detect the sheared fractures at the subsurface. This mode of fracture types resulted in closed fractures filled with filling materials such as ferruginous materials and gypsum. Figure 10 shows a shear fracture which acts as a fluid barrier for fluid movement. The top view of the study area describes three sets of fractures striking E-W, N-S, and NW-SE directions appearing at the cross-sectional view of the paleochannel (Fig. 11).

Fracture fill and fluid barrier

The Rawd Al-Jawa glaciofluvial paleovalley shows three types of fractures, namely, open fractures, closed shear fractures, and resistive to closed fractures filled with gypsum. Figure 12 shows a major shear fracture considered as a discontinuity surface separating two types of sandstone packages

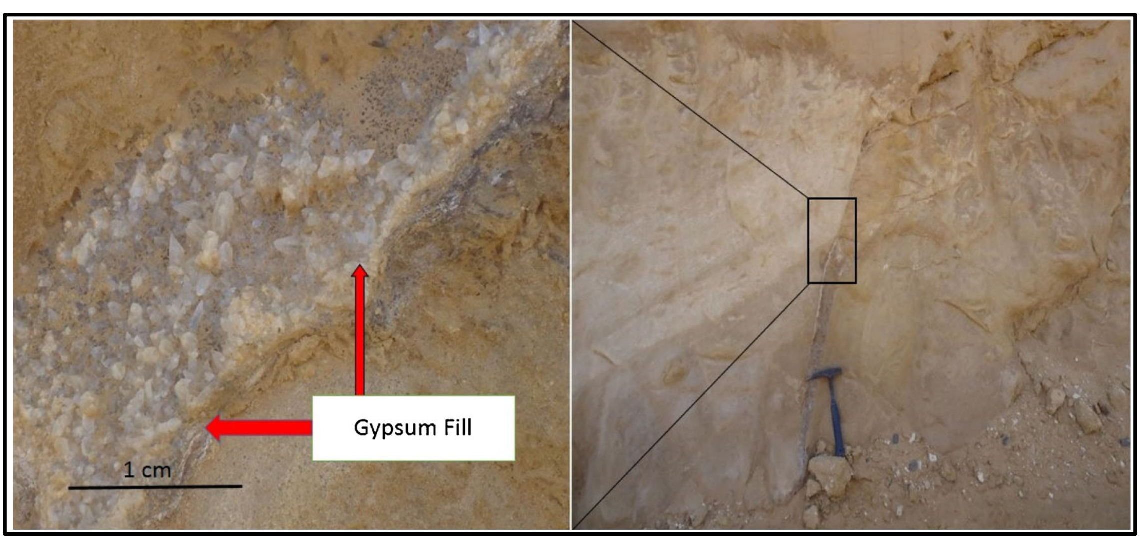

Fig. 13 Fracture fill with digenetic gypsum (resistive fracture) at the Sarah paleovalley

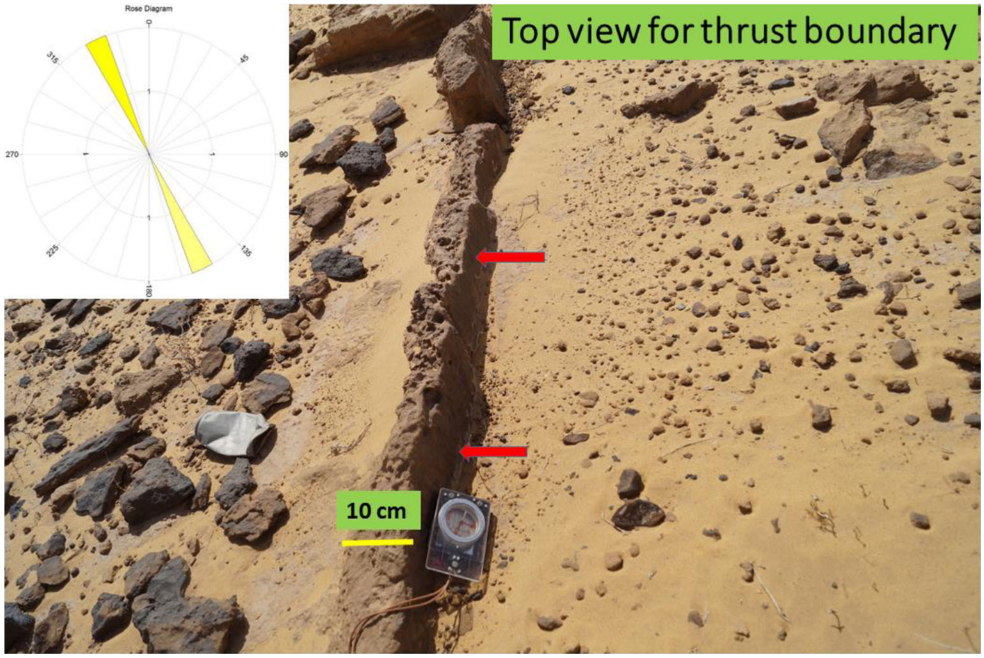

Fig. 14 *Top view* for thrust fracture filled with iron oxides (fluid barrier)

and acting as a fluid barrier against fluid movement. The fractures filled with gypsum are also considered as fluid barriers, and they reduce reservoir quality or positively as seal for hydrocarbons (Fig. 13). The good porosity values and open fractures act positively to increase reservoir quality. All these fracture types occur in the sandstone lithofacies, which consist of sandstone packages from different origins separated by unconformity surfaces. Ferrugination is

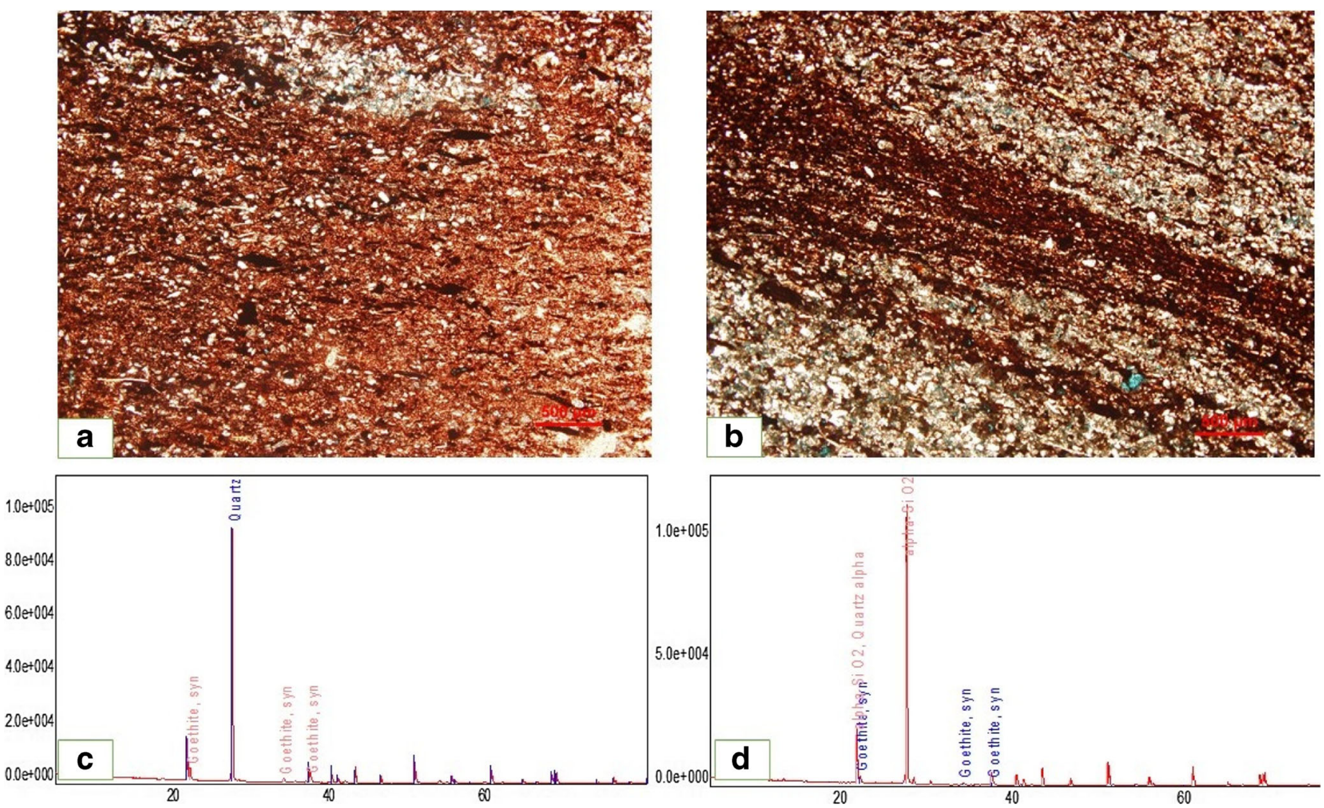

Fig. 15 Thin section and XRD data for the fracture fill for NW-SE closed fractures set showed it consists of quartz and iron oxides

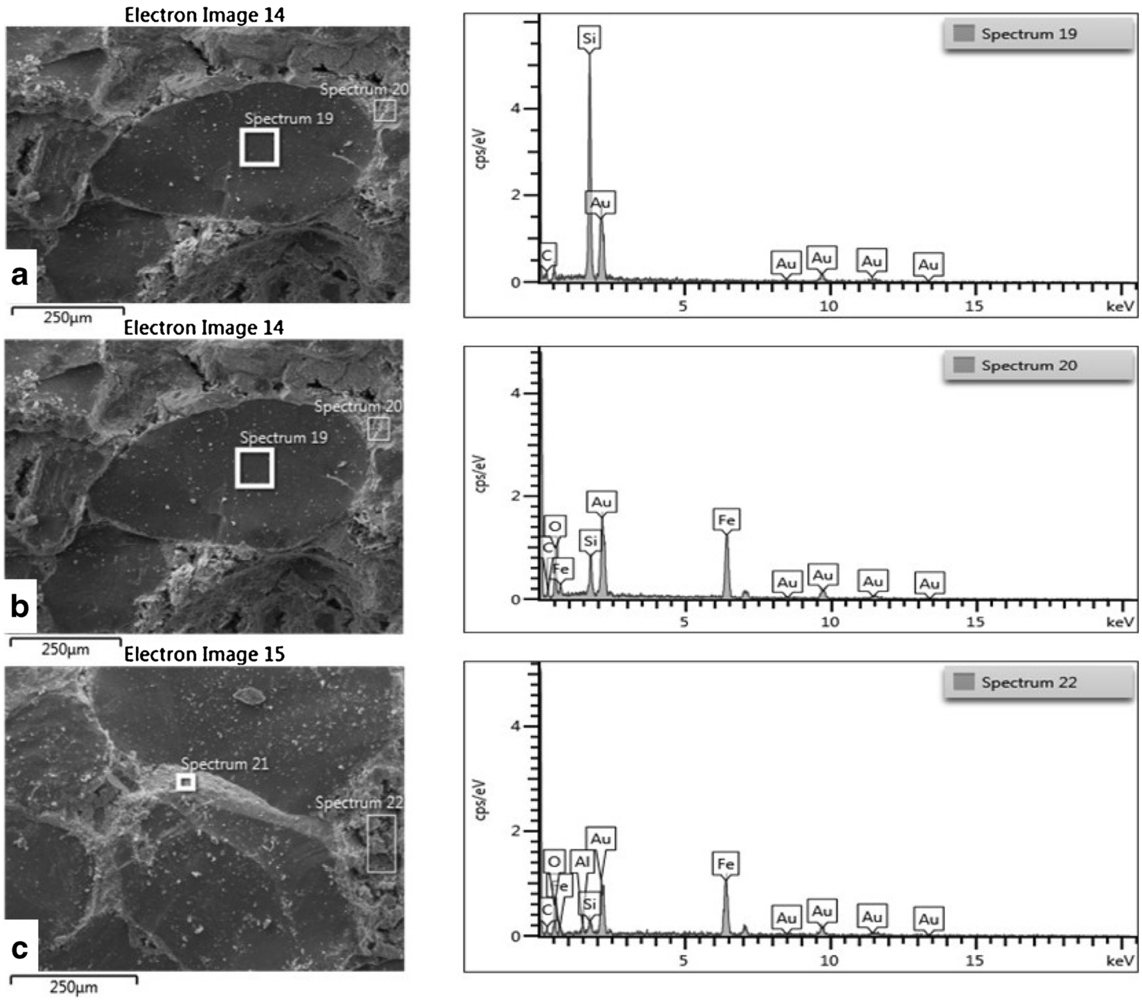

Fig. 16 SEM-EDS data for the fracture fill for NW-SE closed fractures set described the fracture fill and its elemental composition

considered one of the major factors in reducing reservoir quality. This ferruginous sandstone is distributed throughout sandstone lithofacies and on top of the outcrop. Ferrugination occurs in irregular circular shapes on the outcrop, characterized by different sandstone compositions inside and outside the ferruginous boundary, and it is probably due to the concentration of iron oxides and iron-rich grains and/or cement due to movement of iron in aqueous condition. This ferruginous boundary has a thickness from 2 to 10 cm characterized by the absence of porosity and permeability (Fig. 14).

The thin section (Fig. 15) description revealed poorly sorted angular to subangular fractured sandstones with iron oxides as a cementing material for most of the samples which reflect the glacial nature for the Sarah paleochannel. The dominant minerals are quartz in sandstone lithofacies and iron oxides. The thin section of the fracture fill is characterized by crushed and fractured quartz and the presence of iron oxides with lamination nature. The fracture between different glaciofluvial units is considered as a boundary between different glaciation events of sedimentation and filling with crushed and fractured quartz and iron oxides resulting from the friction between different sandstone packages. The SEM-EDS data for the fracture fill shows the presence of crushed quartz and iron oxides as a cement material for the NW-SE closed fracture set (Fig. 16). The thin sections and SEM images describe very low visual porosity. The thickness of the fracture fill may reach up to 10 cm, which may act as a seal in the subsurface and separate different sandstone packages. The XRD data for the fracture fill confirmed the presence of quartz and iron oxides. Fracture and lithological models created for the Sarah paleochannel described fracture set orientations and characteristics and showed the relation between fracture propagation and lithologic units (Fig. 17).

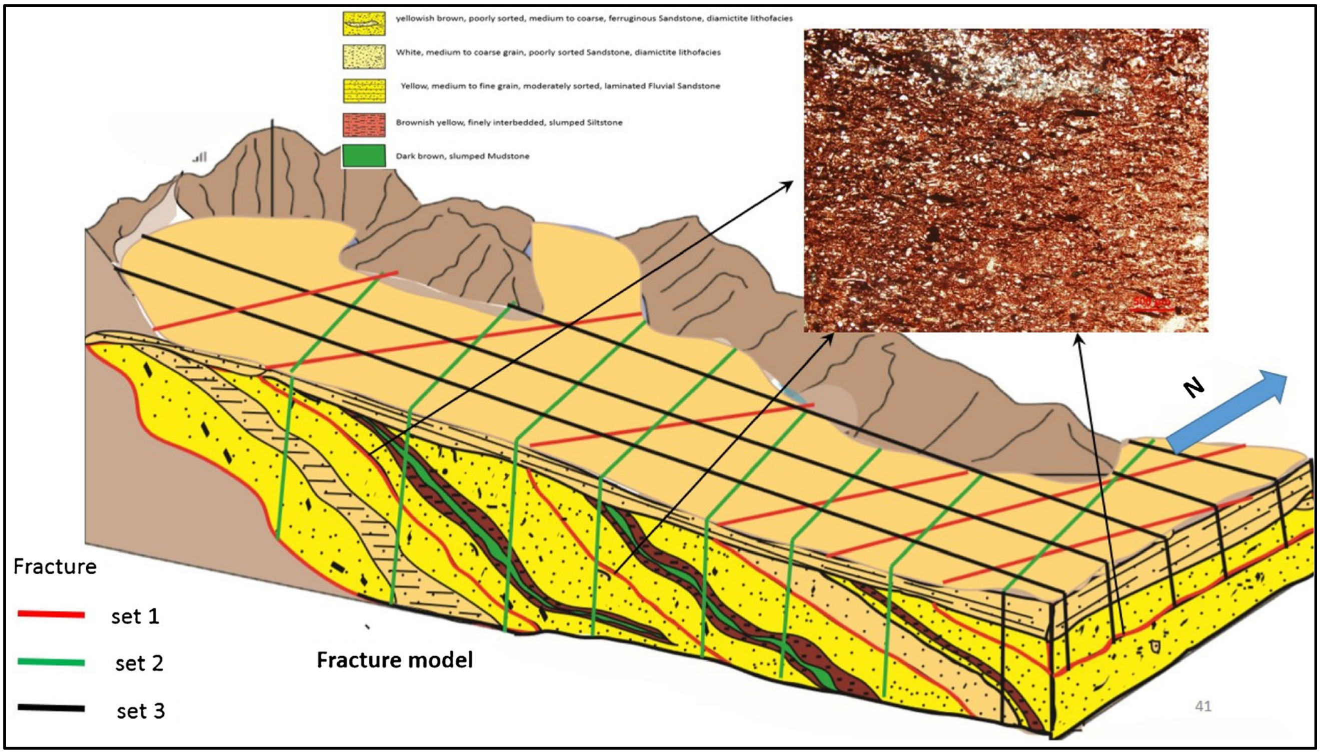

Fig. 17 Fracture and lithological model for the Sarah paleochannel and the relation between fracture propagation and lithologic units. The thin section showed the thrust boundary fracture fill

Conclusion

The Late Ordovician Sarah Formation is composed of glaciofluvial deposits outcropping in central and NW Saudi Arabia. The fracture analysis revealed three types of fracture modes which are mode 1 (opening mode), mode 2 (sliding mode), and mode 3 (shear mode) which all reflect different stress regimes. Both calcite and iron oxides are found as fracture fill for most of the closed to resistive fracture types (mode 2 and mode 3 fracture types). The fracture properties changed from closed, resistive, to open fractures based on mode regime and lithofacies changes. The closed fracture sets mainly resulted from a sliding mode regime. The SEM-EDS and XRD data are used to characterize the fracture fill which showed quartz and iron oxides as filling materials for the SE and NW fracture sets. Some E-W strike fractures showed diagenetic gypsum as fracture fill. The thin section showed very low visual porosity with preferred lineation. The fracture fill may reach up to 10 cm which act as a seal separating between different glacial push moraine sediments in the formation. The closed fracture sets confined mainly to SE-NW fracture sets. The resistive fractures resulted mainly from mode 3 regime, which fills the fractures with calcite and iron oxides. These types of fractures are mainly confined to E-W fractures. The opened fractures resulted from mode 1 regime and are mainly confined to S-N fracture sets, which are enhanced for reservoir quality. The fracture study on the outcrop showed that fracture direction and characterization are well correlated with those reported in the subsurface by Bukhamseen et al. (2010). Structural and lithological models conducted helped to provide a clear understanding for the fracture distribution and their relation to the lithological distribution.

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References

Bartlett E, Vaslet D, Berthiaux A, Le Stat P, Fourniguet J (1986) Geologic map of the Hail quadrangle, sheet 27E, Kingdom of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources. Jiddah, Geoscience Map GM-115C

Bennett MM, Glasser NF (Eds.) (2011). Glacial geology: ice sheets and landforms. Wiley

Bukhamseen RH, Khakimov A, Sierra L, Machala M, Young D (2010) First successful selective tight gas reservoir completion and fracture stimulation in Sarah Formation, Rub Al-Khali Empty Quarter of Saudi Arabia, SPE Russian Oil and Gas Conference and Exhibition, Moscow, Russia

Clark-Lowes D (2005) Arabian glacial deposits: recognition of palaeovalleys within the Upper Ordovician Sarah Formation, Al Qasim district, Saudi Arabia. Proc Geol Assoc 116(3):331–347

Ghienne JF (2011) The Late Ordovician glacial record: state of the art. Ordovician of the World Cuadernos del Museo Geominero 14:13–19

Janjou D, Halawani MA, Al-Muallem MS, Brosse JM, Becq-Giraudon JF, Dagain J, Genna A, Razin P, Roobol MJ, Shorbaji H, Wyns R (1996a) Geologic map of the Tabuk quadrangle, sheet 28B, Kingdom of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources. Jiddah, Geoscience Map GM-137

Janjou D, Halawani MA, Al-Muallem MS, Robelin C, Brosse J-M, Courbouleix S, Dagain J, Genna A, Razin P, Roobol MJ, Shorbaji H, Wyns R (1996b) Geologic map of the Al Qalibah quadrangle, sheet 28C, Kingdome of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources. Jiddah, Geoscience Map GM-135

Kanninen, Popelar (1985) Advanced fracture mechanics. Oxford University Press, Oxford

Konert G, AM Afifi, SA Al-Hajri, K de Groot, AA Al Naim, and HJ Droste (2001) Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate, in Petroleum Provinces of the Twenty First Century: AAPG Memoir 74, p. 483–51

Laboun AA (2010) Paleozoic tectono-stratigraphic framework of the Arabian peninsula. Journal of King Saud University - Science 22(1):41–50 ISSN 1018-3647

Le Heron DP, Craig J, Etienne JL (2009) Ancient glaciations and hydrocarbon accumulations in North Africa and the Middle East. Earth Sci Rev 93(3):47–76

Manivit J, Vaslet D, Berthiaux A, Le Start P, Fourniguet J (1987) Geologic map of the Buraydah quadrangle, sheet 26 G, Kingdome of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources. Jiddah, Geoscience Map GM-114 C

McGillivray JG, Husseini MI (1992) The Paleozoic petroleum geology of central Arabia. Am Assoc Petrol Geol Bull 76(10):1473–1490

Melvin J, Norton A (2013) Advances in Arabian stratigraphy: comparative studies of glaciogenic Juwayl and lower Unayzah strata (Carboniferous–Permian) of Saudi Arabia. GeoArabia 18(1):97–134

Millson JA, Mercadier CGL, Livera SE, Perters J (1996) The lower Paleozoic of Oman and its context in the Evolution of a Gondana continental margin. Journal of Geological Society V. 153, no. 2

Moscariello A, Spaal P, Jourdan A, Azzouni AH (2009) The Ordovician Glaciation in Saudi Arabia—exploration challenges part 1. Geology outcrop, Subsurface, analogues), Search and Discovery article # 50175

Schenk CJ, Pllastro RM (2000) Assessment of undiscovered oil and gas resources of the Great Rub al Khali basin by application of the total petroleum system conept- part 11, the Qusiba Paleozoic Petroleum System. Geoarabia 5:175

Senalp M, and A Al-Laboun (2000) New Evidence on Late Ordovician Glaciation in Central Saudi Arabia. Saudi Aramco Journal of Technology. Spring

Stump TE, and van der Eem JG (1995) Overview of the stratigraphy, depositional environments, and periods of deformation of the Wajid outcrop belt, southwestern Saudi Arabia, in Al-Husseini, M.I., ed., Geo-94, Middle East Petroleum Geosciences Conference: Gulf Petrolink, Manama, Bahrain, v. 1, p. 867–876

Van der Wateren DFM (1995) Processes of glaciotectonism. In: Menzies J (ed) Modern glacial environments: processes, dynamics and sediments. Glacial environments. Butterworth-Heineman, London, pp 309–351

Vaslet D (1989) Late Ordovician glacial deposits in Saudi Arabia: a lithostratigraphic revision of the Early Paleozoic succession. Saudi Arabia Ministry of Petroleum and Mineral Resources, Deputy Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources Professional Papers, no. PP-3, p, 15–44

Vaslet D, Kellogg KS, Berthiaux A, Le Start P, Vicent PL (1986) Geologic map of the Baqa quadrangle, sheet 27 F, Kingdome of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah, Geoscience Map GM-116 C

Vaslet D, Janjou D, Robelin C, Al-Muallem MS, Halawani MA, Brosse J-M, Berthiaux A, Breton J-P, Courbouleix S, Roobol MJ, Dagain J (1994) Geologic map of the Tayma quadrangle, sheet 27C, Kingdome of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources. Jiddah, Geoscience Map GM-134

Williams PL, Vaslet D, Johnson PR, Berthiaux A, Le Start P, Fourniguet J (1987) Geologic map of the Jabal Habashi quadrangle, sheet 26F, Kingdome of Saudi Arabia (with text): Saudi Arabian Deputy Ministry for Mineral Resources. Jiddah, Geoscience Map GM-98C