Reservoir geology and effects on exploitation of natural bitumen deposits (Nigerian deposits as a case study)

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Abstract

Geological investigation have led to discovery of huge tar sand deposits within Afowo Formation of the Turonian–Maastrichtianage (95.9–66.0 Ma) in the Nigerian sector of the Eastern Dahomey Basin. This study aims at determining the feasibility of exploiting the major hydrocarbon resource steam assisted gravity drainage enhanced recovery technique. Samples from three core holes were dry sieved to determine the particle size distribution and their sections studied using a petrographic microscope. Clay mineral content was determined using X-ray diffraction scanning electron microscopy. The granulometric analysis shows the bituminous sediments to be generally fine grained and moderate to well sorted, and the grains are angular to subangular. Porosity ranges from 15.5 to 33.6 ϕ with average value of 26.4 ϕ , while permeability ranges from 270 to 4800 mD, with an average value of 4800 mD (very high) recorded for the sandstones. Petrographic study, scanning electron microscopy and X-ray diffractometry showed quartz as the dominant mineral component, with subordinate feldspar and other accessory minerals. The predominance of quartz is probably due to its mechanical stability. The low frequency of feldspar is attributable to its susceptibility to chemical breakdown and alteration, respectively, during transport and after deposition, with latter accounting for the observed secondary porosity. Kaolinite is the common clay mineral present in the oil sands and may not have sufficiently reduced the reservoir quality to negatively impacting enhanced recovery operation by steam assisted gravity drainage.

Keywords Reservoir · Enhanced recovery · Gravity drainage · Feldspar · Clast

Introduction

The eastern Dahomey basin of the Nigeria sector contains extensive wedge of Cretaceous to recent sediments that thickens towards the offshore up to 3000 m. The basin has been of much geological interest as a result of the occurrences of bitumen, limestone, glass sands and phosphates (Nton 2001).

Exploration for hydrocarbon commenced in this basin in 1908, near Okitipupa, east of Lagos, where bituminous sands outcrop.

Bitumen-impregnated sandstones (tar sand) outcrop in a 120 km by 6 km belt in Southwestern Nigeria from the Okitipupa ridge/ western feather edge of the Tertiary Niger Delta to as far west as Ijebu-Ode in Ogun State, Fig. 1.

The geology of these deposits, oil saturation and reserve estimates as well as textural characteristics of the associated sands have been described (Adegoke et al. 1980, 1981; Enu 1987). The physicochemical properties of the bitumen in relation to production and processing have been studied (Oshinowo et al. 1982; Oluwole et al. 1985). The origin of the bitumen has been discussed (Coker 1990; Ekweozor 1986). Other relevant studies on the deposit and geology of the basin include works done by (Ako et al. 1983; Ekweozor 1986, 1990; Nwachukwu and Ekweozor 1989; Enu 1987, 1990; Enu and Adegoke 1984; Elueze and Nton 2004; Akinmosin et al. 2005, 2013; Akinmosin and Osinowo 2008).

Enu (1985) distinguished two horizons: X (shallow) and Y (deeper than 50 m). The former can be exploited by open cast mining, and the latter by steam-assisted gravity drainage (SAGD).

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Fig. 1 Generalized geological map of the Eastern Dahomey Basin showing area extent of the tar sand deposits. Modified after Enu (1985)

Study area

Based on Fig. 2, the study area is located at 6.55 N, 4.45E; 6.75 N, 4.77 E. Samples used for the project were sourced from three core holes labelled Well X, Well Y and Well Z which, respectively, located in Ayede-Ajgunle with coordinate 6.58 N, 4.62 E, Araromi-Obu/Ago Alaye with coordinate 6.59 N, 4.54 E and Ajgunle with coordinate 6.60, 4.60 E.

Stratigraphy of the Dahomey basin

Table 1 shows stratigraphic succession compiled following the works of Jones and Hockey (1984), Omatsola and Adegoke (1981), and Agagu (1985) who relied at least partly

on earlier studies by Russ (1924) and Reymont (1965). In most part of the basin, the stratigraphy is dominated by sand–shale alternation, with subordinate limestones and clays (Agagu 1985).

Research methodology

Twenty (20) selected core samples were used in this study. The lithological logs of the borehole drilled in each location were generated by logging each borehole.

Representative samples were collected from each lithofacies for laboratory analyses which included: grain size analysis, thin section petrography, X-ray diffractometry (XRD), and scanning electron microscopy (SEM). Table 2 shows the locations of core holes and the depth of analysed samples.

Fig. 2 Location map of the study area

Table 1 Age and stratigraphic relationship of the formations of the Dahomey basin (Adapted and modified by various Authors)

Jones and Hockey (1964)			Omatsola and Adegoke (1981)		Agagu (1985)	
	Age	Formation	Age	Formation	Age	Formation
Quaternary	Recent	Alluvium			Recent	Alluvium
Tertiary	Pleistocene-oligocene	Coastal plain sands	Pleistocene to oligocene	Coastal plain sands	Pleistocene to oligocene	Coastal plain sands
	Eocene	Ilaro	Eocene	Ilaro Oshoshun	Eocene	Ilaro Oshoshun
	Paleocene	Ewekoro	Paleocene	Akinbo Ewekoro	Paleocene	Akinbo Ewekoro
Late Cretaceous	Late Santonian	Abeokuta	Maastrichtian-Neocomian	Araromi-Afowo-Ise	Maastrichtian-Turonian-Neocomian	Araromi Afowo Ise
Precambrian crystalline basement rock						

Grain size analysis

For textural analysis, 100 g of the prepared samples were dry-seived using vibrating sieving machine for 15 min with sieves of the following mesh sizes: 2 μm , 1.4 μm , 1 μm , 0.5 μm , 0.25 μm , 0.18 μm , 0.125 μm , 0.09 μm , 0.075 μm , 0.063 μm and pan, corresponding to -1Φ , -0.5Φ , 0Φ , 1Φ , 2Φ , 2.5Φ , 3Φ , 3.5Φ , 3.75Φ , 4Φ and 5Φ on the logarithmic scale values, respectively. The individual cumulative weight with their percentages was determined. These data were used to plot histograms and cumulative frequency curves for individual samples on arithmetic and semi-log graphs. The parameters were computed using moment statements mean, mode, standard

deviation, kurtosis, and skewness (using formulae by Folk and Ward 1957).

Thin section preparation

Thin section preparation was carried out at the Geological Laboratory of the Obafemi Awolowo University Ile-Ife, Nigeria. The sample was placed in a container and Canada balsam spread on the sample. The sample was then placed on a hot plate and heated for about 15 min subsequently removed and left overnight (to solidify). The next day, the sample was placed and cut on a lapping slide glass, was left for 24 h. The araldite allowed the sample to stick to the surface of the glass /mounting slide. The

Table 2 Core holes and samples depths

Location X (Ayede-Ajgunle)	Location Y (Araromi- Obu/Ago-Alaye)	Location Z (Ajgunle A4)
Depth 54–57 m	Depth 15–18 m	Depth 54–57 m
Depth 69–72 m	Depth 24–27 m	Depth 63–66 m
Depth 72–75 m	Depth 33–36 m	Depth 75–78 m
Depth 75–78 m	Depth 39–42 m	
Depth 90–93 m	Depth 57–60 m	
	Depth 60–63 m	
	Depth 66–69 m	
	Depth 69–72 m	
	Depth 72–75 m	
	Depth 75–78 m	
	Depth 81–84 m	
	Depth 84–87 m	

sample was grounded with the use of a grinding machine to a considerable thickness. The grinded sample was then placed on the lapping slide with the use of microscope. This was to ensure that the sample was not too thick or thinly prepared so that the minerals can be seen visibly. This is then covered back with silicon carbide, cover slide and Canada balsam on the lapping slide. This was placed on the hot plate for about 15–20 min and left to get cold for about 1 h. The sample was then washed with acetone and water with detergent and left to dry before it was labelled.

Laboratory analysis: XRD

XRD analyses was carried out at the Nigerian Geological Research Laboratory (NGRL) in Kaduna, Kaduna State. The NGRL Kaduna uses Empyrean diffractometer DY 674 (2010) with a copper anode material manufactured by Analytical Holland. It works with a combination of other components such as the water chiller which cools the X-ray tube and maintains a uniform temperature. There is also the compressed air that helps in opening and closing of the cabinet door. The goniometer forms the central part of the Empyrean diffraction system. It contains the basic axes in X-ray diffractometry: the omega and 2 theta axes. The X-ray tube, incident beam optics, the sample stage and the diffracted beam optics including the detector are mounted on specific positions on the goniometer. The goniometer is set up in vertical mode and can be configured for theta–theta and alpha-1 diffraction geometries. The goniometer radius is 240 mm. The diffractometer consists of three basic elements: an X-ray tube, a sample holder, and an X-ray detector.

Laboratory analysis: SEM

The model used for the SEM analysis was SEM-Aspex 2300 (Fig. 12). Vent system by lifting the lever on the left side of the microscope; wait for the drawer to drop. The machine has a chamber with a stage inside it and a tube that is also attached. The stage is divided into segments; the segment used for this analysis is 3 by 3. There is also a magnifying lens used to view the microstructure of the clay sample. There are different interphases using a program perception model. There is beam energy (acceleration voltage) of 15 kV; the filament is driven at a percentage of 66.9% of the total voltage which results into current flow. The emission current is 50.7 μA . It is set to different magnification. The stage is divided into X, Y, Z. The beam: beam energy, filament drive, emission current. The vacuum has interlock which has to read ready before scanning and the pressure must be at 3.2×10^{-5} torr. The pressure must be at least 5×10^{-5} torr. Sample pressure is set to high vacuum for images to be seen.

Result and discussion

Lithological descriptions of the core samples from the study area

Lithological description of the study area was based on core samples collected from the three locations. The columnar lithological descriptions of the studied wells are shown in Figs. 3, 4 and 5 respectively.

Grain size analysis

Textural parameters such as roundness, sphericity, grain size and sorting, derived from granulometric analysis, can be used to correctly deduce the provenance of sediments and further characterize the reservoir. The use of grain shape to identify sedimentary environments assumes that grain morphology reflects environmental history (Krinsley and Doornkamp 1973; Bull 1981). Table 3 shows a comprehensive result of the grain size analysis carried out on the analysed samples.

Deductions from grain size analysis

Data from both the lithological description and granulometric (sieve) analysis confirmed that the core samples for Ayede-Ajgunle location (Well X) range from fine to very fine grained sizes (Fig. 6). However, samples at depths between 69 and 72 m have their grain sizes ranging from medium grained to very fine grained. The grains are

Fig. 3 Litho-section of core samples at Ayede-Ajgunle (Well X)

moderately sorted to very well sorted, symmetrical skewed and platykurtic to mesokurtic (90–93 m).

The particle size for core samples from Araromi-Obu/ Ago-Alaye (Well Y) range from fine to very fine grain sizes. The grains are generally moderately sorted, symmetrical to strongly coarse skewed and mesokurtic to very platykurtic. Similarly, the sediments in this location show a relatively narrow range of grain size (2.400–3.101). This also suggests that the sandstones of this location are relatively closer to the distal portion of the basin as compared to the proximal portion. The close range of grain sizes, also depicts a single source of sediment supply as it is been revealed by the predominant unimodal.

The particle size for core samples from Ajgunle A4 (Well Z) are generally fine grained. The grains are moderately sorted, fine skewed and platykurtic. In the same vein, the grain size ranges of Ajgunle are also of close range to each other (Fig. 7).

Petrographic analysis

Thin section analysis was carried out on the sandstones of the study area to further describe the textural parameters of the samples, their composition, cementing materials, as well as grain contacts. The following mineralogical compositions were identified from the petrographic study:

Quartz Thin section petrographic analyses revealed quartz as the predominant mineral (Table 4). Its dominance cuts across the three bore hole (core) samples (Figs. 8, 9) of the present study. The dominance of quartz minerals, relatively gave the sandstones of the study area a kind of mechanical stability.

Feldspar Unlike quartz, Feldspar minerals were poorly represented (Table 4). In comparison to other minerals, detrital feldspar was generally low (Figs. 10 and 11). Like quartz mineral, its low percentage, cuts across the three

Fig. 4 Litho-section of core samples at Araromi-Obu/Ago-Alaye (Well Y)

core samples location. Detrital feldspars, contributed to some of the diagenetic alteration in the study area.

Micas Mica grains make up some of the accessory minerals observed in the study area. However, it was generally low in percentage in the entire study area (Figs. 12 and 13).

Rock fragments Rock fragments in the whole study area was generally low (Table 4).

X-ray diffraction (XRD) and clay minerals analyses

The different sandstone samples of the Afowo Formation analysed consist dominantly of quartz and kaolinite. Subordinate amounts of syvite (KCL), montmorillonite, gypsum, calcite and jarosite ($\text{KFe}^{3+}_3(\text{SO}_4)_2(\text{OH})_6$) were found. A representative diffractogram of one of the analysed sample is shown in Figs. 14 and 15.

Fig. 5 Litho-section of core samples at Ajegunle A4 (Well Z)

Scanning electron microscopy (SEM)

Scanning electron microscopy was used to identify the clay species, examining the orientation of clay to framework grains and to identifying features, such as pores, that cannot be seen under the petrographic microscope (Fig. 16).

The occurrence of clay minerals adversely impacts the permeability and porosity of a reservoir rock. Clays can occur as matrix, grain coatings, clay intraclasts and replacement grains. Thus, clays can completely occlude the porosity if they occur as matrix, or hinder the permeability if they occur as grain coatings. Factors such as the source rock, type of weathering and depositional environment can determine the primary clay mineralogy and habit in the sediments. Other factors related to the sandstone composition,

its diagenetic evolution, burial/thermal histories can also determine the clay type in the sandstones.

Data from petrographic, and SEM analyses document a diagenetic sequence. The following diagenetic features were recognized; quartz-overgrowth, calcite cement and pore-filling kaolinite. XRD analysis, reveals not only the presence of calcite cement, but also minor calcite occurrence. These features strongly indicate that porosity in these sandstones is partly secondary in origin. Preservation of high porosities after the dissolution of grain-supporting carbonate cements suggests that the pressure seal became effective about the same time that carbonate cement began to dissolve.

Quartz overgrowth surfaces examined under SEM reveal a network of ridges that form a box work texture suggestive

Table 3 Results of grain size analysis

S/N	Sample no.	Mean	Standard deviation	Skewness	Kurtosis	Interpretation
1	Loc X (69–72)	2.594	1.039	−0.045	0.759	Fine sand, poorly sorted, symmetrical, platykurtic
2	Loc X (72–75)	2.891	0.753	0.098	0.694	Fine sand, moderately sorted, symmetrical, platykurtic
3	Loc X (75–78)	2.656	0.936	0.049	0.740	Fine sand, moderately sorted, symmetrical, platykurtic
4	Loc X (90–93)	2.400	1.062	0.069	1.054	Fine sand, poorly sorted, symmetrical, mesokurtic
5	Loc Y (15–18)	2.971	0.732	0.040	0.733	Fine sand, moderately sorted, symmetrical, platykurtic
6	Loc Y (33–36)	3.080	0.974	0.724	0.912	Fine sand, moderately sorted, symmetrical, platykurtic
7	Loc Y (39–42)	3.101	0.924	−0.703	0.844	Very fine sand, moderately sorted, very coarse skewed platykurtic
8	Loc Y (60–63)	2.656	0.936	0.049	0.740	Fine sand, moderately sorted, symmetrical, platykurtic
9	Loc Y (66–69)	2.512	1.043	0.019	1.099	Fine sand, poorly sorted, symmetrical, mesokurtic
10	Loc Y (69–72)	2.640	1.021	−0.074	0.779	Fine sand, poorly sorted, symmetrical, platykurtic
11	Loc Y (72–75)	2.596	0.925	0.127	0.771	Fine sand, moderately sorted, fine skewed, platykurtic
12	Loc Y (75–78)	2.901	0.680	0.251	0.602	Fine sand, moderately well sorted, fine skewed, very platykurtic
13	Loc Y (81–84)	2.613	1.056	−0.074	0.883	Fine sand, poorly sorted, symmetrical, platykurtic
14	Loc Y (84–87)	2.971	0.732	0.040	0.733	Fine sand, moderately sorted, symmetrical, platykurtic
15	Loc Z (75–78)	2.860	0.758	0.128	0.702	Fine sand, moderately sorted, fine skewed, platykurtic

Fig. 6 Grain shape and size as observed from the petrographic microscope from Well X at a depth of 54–57 m **Fig. 7** Sorting and cement development as seen under petrographic microscope for Well Z at a depth of 54–57 m

of local quartz dissolution (Fig. 17). Carbonate cement dissolution textures are observed in few samples (Fig. 18) while in thin section, patches of discontinuous calcite cement with synchronous extinction are observed, suggesting a

Fig. 8 Quartz grain in Araromi-Obu/Ago-Alaye at depth 57–60 m under crossed polarised light (i.e. nicol). *Qtz* quartz, *Por* pore space **Fig. 9** Quartz grain in Araromi-Obu/Ago-Alaye at depth 81–84 m under crossed polarised light (i.e. nicol). *OPMN* opaque mineral, *PDF* partial dissolution of feldspar, *POR* pore space

Table 4 Frequencies of the framework elements and binding material

S/N	Sample no.	Framework component			Binding material	
		Quartz (%)	Feldspar (%)	Rock Fragment (%)	Matrix (%)	Cement (%)
1	X 54–57	90.4	6.0	3.6	3	5
2	X 69–72	94.1	2.4	3.5	3	6
3	X 72–75	93.0	3.5	3.5	4	6
4	X 75–78	90.4	6.0	3.6	4	6
5	X 90–93	94.1	2.4	3.5	4	6
6	Y 15–18	90.7	5.8	3.5	3	4
7	Y 24–27	90.9	5.7	3.4	3	4
8	Y 33–36	94.0	2.4	3.6	3	4
9	Y 39–42	95.2	2.4	2.4	3	4
10	Y 57–60	93.3	2.7	4.0	4	4
11	Y 60–63	92.9	3.6	3.6	4	5
12	Y 66–69	94.1	2.4	3.5	4	5
13	Y 69–72	94.0	2.4	3.6	4	6
14	Y 72–75	93.3	4.0	2.7	4	6
15	Y 75–78	92.9	3.6	3.6	4	6
16	Y 81–84	95.2	2.4	2.4	4	6
17	Y 84–87	92.6	3.7	3.7	4	6
18	Z 54–57	92.6	3.7	3.7	4	5
19	Z 63–66	94.1	2.4	3.5	4	6
20	Z 75–78	92.9	3.6	3.6	4	6

Fig. 10 a, b Feldspar grain particularly orthoclase in Araromi-Obu/ Ago-Alaye at depth 60–63 m and 75–78 m, respectively, under crossed polarised light (i.e. nicol). *INTPOR* interconnected pore

space, *OPMN* opaque mineral, *PDF* partial dissolution of feldspar, *Por* pore space, *QNZ* quartz

Fig. 11 a, b Showing Plagioclase Feldspar grain in Ajegunle A4 at depth 63–66 m under plane polarised light (PPL) and at Ajegunle A4 at depth 75–78 m under cross polarised light (Nicol)

Fig. 12 a, b Biotite in Araromi-Obu/Ago-Alaye at depth 81–84 m under plane polarised light (PPL) and at Ajegunle A4 at depth 54–57 m under plane polarised light (PPL)

previous connectivity that was disrupted by dissolution. Kaolinite occurs locally in normally pressured, high-porosity

sandstones and typically fills illite lined pores in samples that exhibit intergranular grain penetration. Authigenic illite

Fig. 13 a, b Showing accessory mineral particularly apatite grain in Ayede-Ajgunle at depth 75–78 m under plane polarised light (PPL) and at Araromi-Obu/Ago-Alaye at depth 84 m under plane polarised light (PPL)

Fig. 14 XRD diffractograms of core sample from Ajgunle A4 at a depth range of 75–78 m

often occurs as a fibrous pore-filling mineral which strongly reduces the permeability in reservoir sandstones.

Porosity and permeability

The high porosity noted in the study area is attributable to the dissolution of minerals principally kaolinite and to the early precipitation of iron oxide cement which prevented further significant compaction (Christopher et al. 2017).

The porosity and permeability data were derived empirically since sample size did not meet the criteria for measurement using the permeameter and porosimeter. The values range from 15.5% (medium) to 33.6% (very high), as seen in the Table 5, the porosity value decreases with depth except for Well X at a depth of 90–93 m. This is probably due to complete dissolution of feldspar grain at high temperature and pressure due to overburden (Baiyegunhi et al. 2017). Permeability ranges from 270 mD (low) for the sandy shales

Fig. 15 XRD diffractograms of core sample from Araromi-Obu/ Ago-Alaye at a depth range of 81–84 m

Fig. 16 SEM photomicrograph for Ayede-Ajgunle at depth range of 54–57 m. *F* fracture, *FL* fracture line, *MP* micro pores, *SK* sheet kaolinite, *KF* K-feldspar, *VK* vermiform kaolinites. Magnification **a**= $\times 50$, **b**= $\times 100$, **c**= $\times 750$, **d**= $\times 2500$

to 4800 mD (medium) for the sandstones. The results of the porosity and permeability determination are shown in Table 5.

Generally, the porosity in the study area showed no distinct trend. This is probably due to shallow depth which is

still within the eogenetic stage (i.e. early stage diagenesis or shallow diagenesis) and or dissolution of minerals which majorly accounted for the secondary porosity noticed. These features were observed in Well X at depth range 69–72 m,

Fig. 17 Quartz overgrowth in Ayede Ajegunle at a depth range of 63–66 m. *QO* quartz overgrowth. Magnification = $\times 100$

90–93 m, Well Y at depth range of 60–63 m, 66–69 m, 75–78 m and Well Z depth range 63–66 m and 75–78 m.

Conclusion

Due to the high viscous forces retaining tar within the reservoir pores, heavy crudes are often characterised by extremely low mobility under reservoir conditions. Consequently, successful in-situ techniques, primarily thermal methods, are premised on downhole reduction of the viscosity. Steam-based processes, most of which generate steam by burning fossil fuels, currently account for some 98% of commercial production from thermal techniques.

Success of steam-assisted gravity drainage technique among other things, depends largely on the textural attributes of the reservoir as well as on clay types. These in turn determine the quality of porosity and permeability of such reservoir. Inclusion of clays that are vulnerable to swelling when in contact with water affects the success of this technique. The study has, however, shown that some of these types of clay though present, are not well formed.

Fig. 18 Development of calcite in the analysed sample. *C* calcite

Table 5 Side wall core analysis result with the porosity and permeability values

Serial number	Well	Depth (m)	Horizontal permeability (mD)	Horizontal porosity (ϕ)	Lithological description
1	X	54–57	1000	20.2	Shale, v dk gry, fis
2		69–72	3500	30.8	Shly Sst, f/med/coarse, ang, poorly srted, poorly cmt
3		72–75	2700	29.7	Shly Sst, f/med, sang/subr, mod srted, poorly cmt
4		75–78	1100	26.2	Shly Sst, vf/f, subr/rd, mod srted, poorly cmt
5		90–93	4700	33.4	Sst, f/med, subr/rd, mod srted, poorly cmt
6		15–18	2760	26.2	Shly Sst, f, subr/r, v wl srted, poorly cmt
7		24–27	1200	20.2	Muddy, contain high % shale, shaly sst
8		33–36	4500	31.2	Shly Sst, vf/f, subr, mod srted, poorly cmt
9		39–42	1100	26.2	Shly Sst, vf/f, subr, wl srted, poorly cmt
10	Y	57–60	1000	18.5	Shaly sst, vf/f, subr, wl srted, poorly cmt
11		60–63	2760	31.9	Sst, vf/f, sang, wl srted, poorly cmt
12		66–69	4800	33.6	Sst, f, subr/rd, v wl srted, poorly cmt
13		69–72	3500	30.8	Shly Sst, vf/f, sang, mod srted, poorly cmt
14		72–75	270	20.8	Shly Sst, vf/f, subr, mod srted, poorly cmt
15	Z	75–78	4800	33.6	Sst, vf/f, subr, mod srted, poorly cmt
16		81–84	4600	30.3	Sst, vf/f, subr, mod srted, poorly cmt
17		84–87	4700	33.4	Sst, vf/f, subr, mod srted, poorly cmt
18		54–57	270	15.5	Shaly sst, vf/f, subr, wl srted, poorly cmt
19		63–66	270	16.1	Shaly sst, vf/f, subr, wl srted, poorly cmt
20		75–78	340	18.9	Shly Sst, f, rd, v wl srted, poorly cmt

Consequently, this technique will no doubt be suitable for recovery of the Nigerian oil sand deposits. Although, the need for considering the cost implication should still not be down played.

Moreover, data from petrographic and SEM analyses create graphic view of the diagenetic sequence of the studied samples. The following diagenetic features were recognized; quartz-overgrowth, calcite cement and pore-filling kaolinite. XRD analysis, reveals not only the presence of calcite cement, but also minor calcite occurrence. These features strongly indicate that porosity in these sandstones is partly secondary in origin. Preservation of high porosities after the dissolution of grain-supporting carbonate cements suggests that the pressure seal became effective about the same time that carbonate cement began to dissolve.

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