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DIAGENETIC CONTROL ON THE PETROPHYSICAL PROPERTIES OF ALBIAN-CENOMANIAN SANDSTONES IN THE IVORIAN BASIN, WEST AFRICA

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ABSTRACT: This paper presents the results of the detailed petrographical analysis of sandstone samples from three wells from the offshore Ivorian Basin. The study reveals the presence of three types of sandstones in the Albian – Cenomanian succession, namely subarkoses, arkoses and lithic arenites, with dominant detrital minerals comprising quartz, feldspar and lithic fragments. The main authigenic minerals comprise calcite, siderite, silica, kaolinite and pyrite, while the key diagenetic events include compaction, dissolution and recrystallization of feldspar, neoformation and replacement of feldspar, and finally cementation. Primary pore spaces are reduced or occluded by calcite, silica, siderite and pyrite. Secondary porosity was created locally from the dissolution of feldspars but has been partly reduced by authigenic kaolinite. The presence of illitized kaolinite overgrowths and dissolved feldspars, together with significant quartz and the mainly concavo-convex and stylolithic contacts between quartz grains, suggest that the Albian-Cenomanian sandstones of the Ivorian Basin have reached an advanced stage of diagenesis. These diagenetic processes affect petrophysical values which varied as a function of depth.

KEYWORDS: Sandstone, diagenetic, porosity, permeability, Cenomanian, Albian.

1 INTRODUCTION

Albian and Upper Cretaceous sandstones form the main target of petroleum exploration in in the Ivorian Basin as they host substantial gas and oil volumes in a number of fields across the margin. There are significant vertical and lateral variations in sandstone composition and reservoir quality throughout the drilled Cretaceous succession, therefore detailed petrographical characterization of sandstone mineralogy and pore types integrated with petrophysical data forms a key requirement of reservoir description studies from this area.

On the Ivorian Margin, oil exploration has intensified since the initial discoveries in the shelfal region during the 1970s (Petroci & Beicip, 1990) leading to a renewed interest in detailed reservoir facies evaluation. A number of core-based sedimentological studies have been performed in recent years (Yao, 2012, Assale, 2013, Mobio, 2017; Ouattara et al., 2016) together with several multi-well regional reservoir studies (Bessong, 2012; Core Lab, 2011; Core Lab, 2014). Furthermore, as part of a concerted effort to improve understanding of reservoir development and reservoir quality controls in the region, PETROCI (National Company of Petroleum Operations of Ivory Coast) in recent years has promoted the in-house use of multiple reservoir description techniques, with particular focus on cored intervals.

There is little public domain data available documenting core-based petrophysical values in Ivorian reservoir intervals and therefore the aim of this paper is to present the results of a recent reservoir description study evaluating diagenetic controls on petrophysical properties in Albian-Cenomanian sandstones from three offshore Ivorian Basin wells. The wells were drilled by Esso in 1978 and 1982 in the central to eastern part of the basin (along the Abidjan segment of the margin) but well names have been changed to maintain confidentiality (Figure 1: FE-1, FE-2 and FE-3).

2 EQUIPMENT AND METHODOLOGY

This study is based on petrographical and petrophysical analysis of a total of 272.5 metres of conventional core material from the three offshore Ivorian Basin wells, including 195.94 m of core from the FE-1 well, 12.70 m from FE-2 and 63.90 m from FE-3. An accompanying paper has been prepared documenting the sedimentological characteristics of these cores (Fea *et al.,* 2018, in preparation).

For the petrophysical component of the study, a pressure decay profile permeameter (PDPK-400^{TM}) was used to acquire permeability values by direct measurement on the slabbed core surface. This equipment provides a precise method for rapidly determining core permeability and heterogeneity and can be used to identify and quantify thin highly permeable beds, permeability barriers and depositional/diagenetic features. The permeameter software was calibrated using measured core plug values and total porosity from the downhole neutron log. Measurements were taken at core intervals and the detailed permeability profile was then imported into the WellCADTM core description logs for each of the three wells.

Permeability in this study is classified as follows: negligible for values below 1 mD (K <1 mD); low for values between 1 mD and 10 mD; average for values between 10 mD and 50 mD; good for values between 50 mD and 100 mD; very good for values between 100 mD and 1000 mD and excellent for values above 1000 mD (Darcy, 1856).

These values are reported as a function of the depth in the cores descriptions formatting software WELLCAD. In this software, for similar permeability measurement values over a given depth, the values were mapped to the Neutron log.

Porosity is values are classified as low for values between 5% and 10%, average between 10% and 15%, good between 15% and 20%, very good between 20% and 30% and excellent greater than 30% (Choquette and Pray, 1970).

Thin section petrographical descriptions in this study follow Dott's classification, modified by Pettijohn *et al.* (1972), with analysis focused on lithological description, grain size (Wenthworth, 1922) and sorting (Maurice, 2003).

Rock chips of about 2 grams mounted on studs, previously metallized with carbon, were examined using a Scanning Electron Microscope coupled with Energy Dispersion Spectrometry (SEM-EDS) to obtain 3D images. This technique makes it possible to analyze the intragranular microporosity or that of the link phase; as well as the arrangement of the clay particles in the pores.

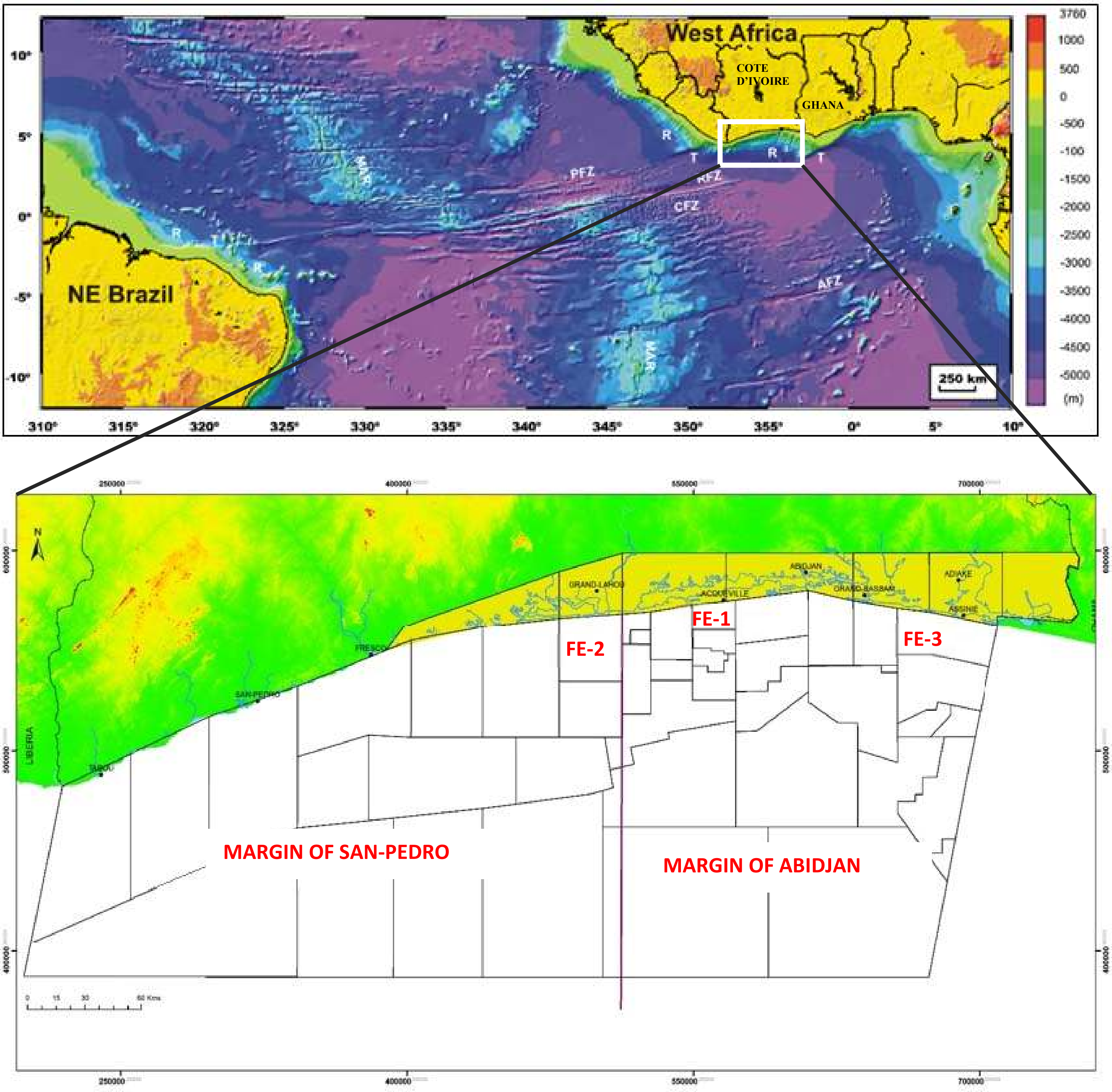

Fig. 1. Geographical location of the studied wells

3 RESULTS AND INTERPRETATIONS

3.1 PETROPHYSICAL MEASUREMENTS

3.1.1 PERMEABILITY

Permeability measurements various in the sandstone facies revealed 303 permeability values measured in the FE-1 well, 128 in the FE-2 well and 433 in the FE-3 well. The distribution diagram of permeability versus depth shows a general decrease in permeability values versus depth (Figs. 2, 3 and 4).

In the FE-1 well, these values vary from 0.00328 mD to 864 mD between the 1900 and 2300 m depth, and from 0.00324 mD to 11.8 mD between 3000 and 3100 m. In the FE-2 well, they vary from 98.6 to 1140 mD between 2590 and 2600 m and from 0.00362 to 7.24 mD between 2660 and 2672 m. Finally, in the FE-3 well, they vary from 0.151 mD to 272 mD between

2380 and 2430 m and from 0.00842 mD to 8.99 mD between 2580 and 2630 m. These values are good to very good and only between 1900 and 2300 m in FE-1well and between 2380 and 2430 m in FE-3 well. Good to excellent values are between 2590 and 2600 m in FE-2 well.

The variations of these permeability values are a function of several parameters, namely the volume of the detrital grains, the size of the grains, the rate of clays, the content of limestone cement and the physicochemical conditions. Thus, the decrease in permeability with depth would be due to the increasing volume of siliceous cement due to the influence of temperature. However, the permeability also varies within the same depth range in conjunction with quartz cementation. The chemistry of diagenetic fluids (salinity and pH) can also influence the volume of quartz cement, thus the permeability. Indeed, a small volume of quartz cement increases salinity and pH.

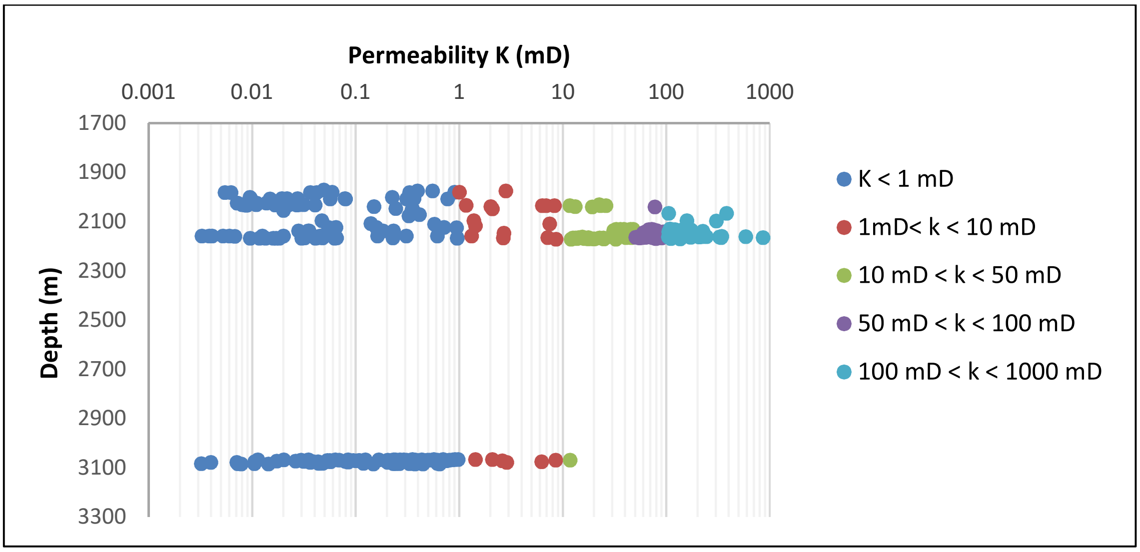

Fig. 2. Diagram of permeability variation versus depth in the FE-1 well

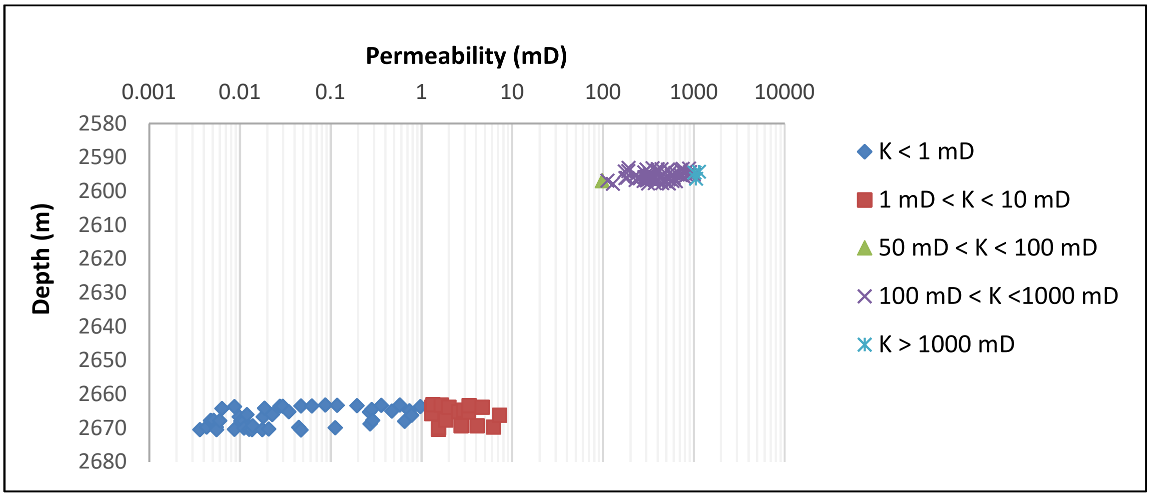

Fig. 3. Diagram of permeability variation versus depth in the FE-2 well

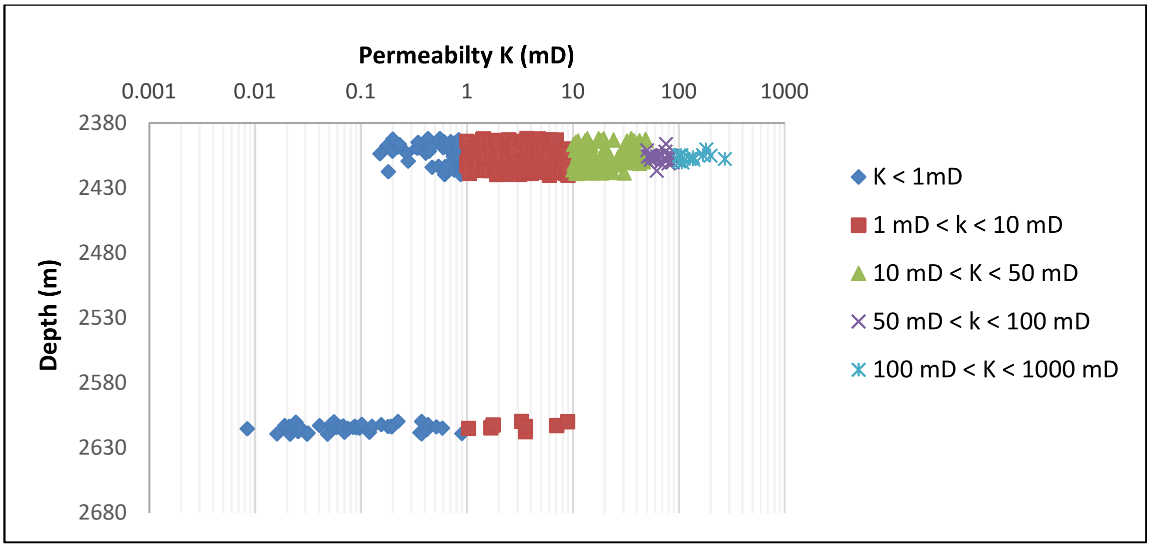

Fig. 4. Diagram of permeability variation versus depth in the FE-3 well

3.1.2 Porosity

Porosity measurements various in the sandstone facies also revealed 303 values in the FE-1 well, 128 in FE-2 and 433 in FE-3. The distribution diagram of these measurements versus depth shows a general decrease in the values of the porosity (Figs 5, 6 and 7).

In the FE-1 well the values of porosity vary from 5.9 to 42% between 1900 and 2300 m and from 10.2 to 29.9% between 3000 and 3100 m. In the FE-2 well, they vary from 21.13 to 24.82% between 2590 and 2600 m and from 4.8 to 26.19% between 2660 and 2672 m. Finally, in the FE-3 well they range from 8.47 to 31.06% between 2380 and 2430 m and from 5.87% to 26.49% between 2580 and 2630 m.

These porosity values appear to be related to the influence of detrital grain size, quartz cement and compaction on the spatial distribution of pores. They also vary with the compaction, the silicification rate of the particles and the thickness of the quartz overgrowths compared to the size of the original detrital grains.

Indeed, porosity values are low in compacted sandstones where intergranular quartz dissolution and pore-filled quartz cement sometimes occlude all the intergranular pores, and the pores are thus isolated. On the contrary, thin overgrowth around poorly compacted detrital grains makes it possible to keep the pores fairly numerous and connected (Fig. 9 C, D). Therefore, more the abundance aureole of overgrowths is abundant around the detrital grains, more the morphology and the geometry of the pores are controlled by the characteristics of quartz overgrowths.

Overall, the most frequent porosity intervals in the three wells studied are between 20 and 30%. Their decrease towards the deep levels reflects a diagenetic control on the petrophysical properties.

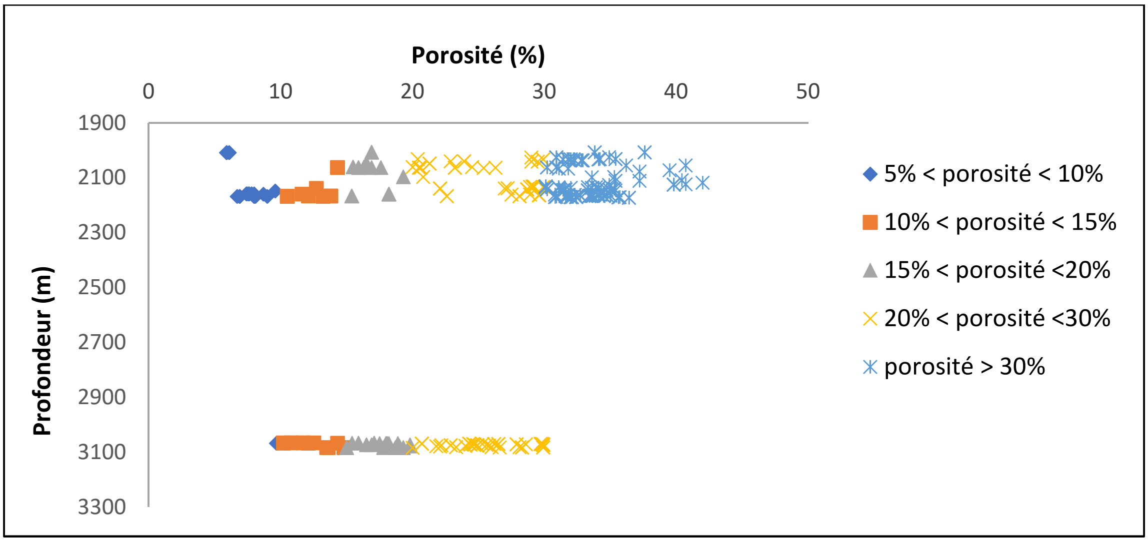

Fig. 5. Diagram of porosity variation versus depth in the FE-1 well

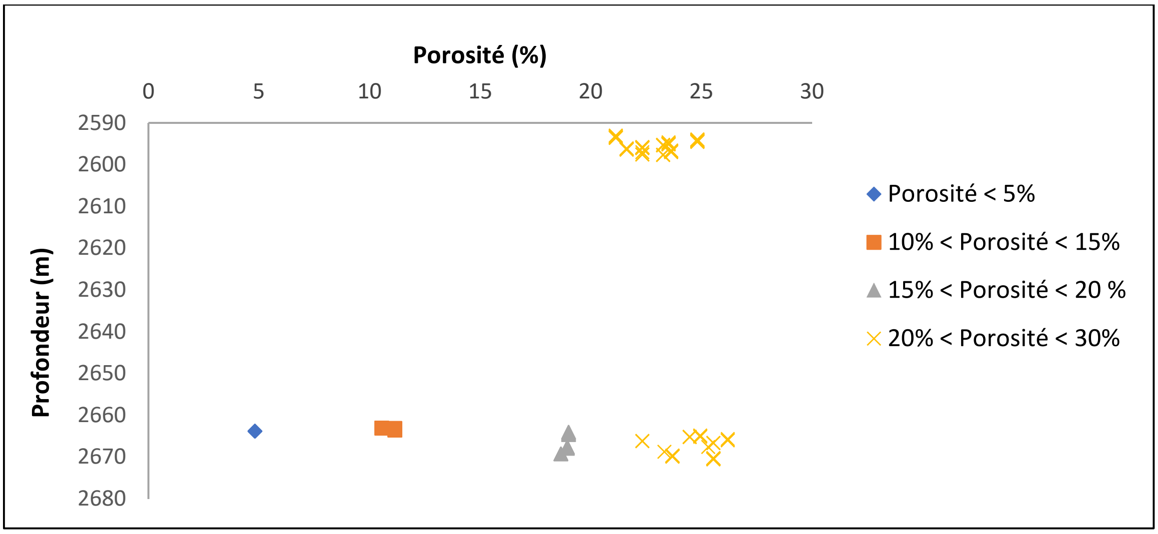

Fig. 6. Diagram of porosity variation versus depth in the FE-2 well

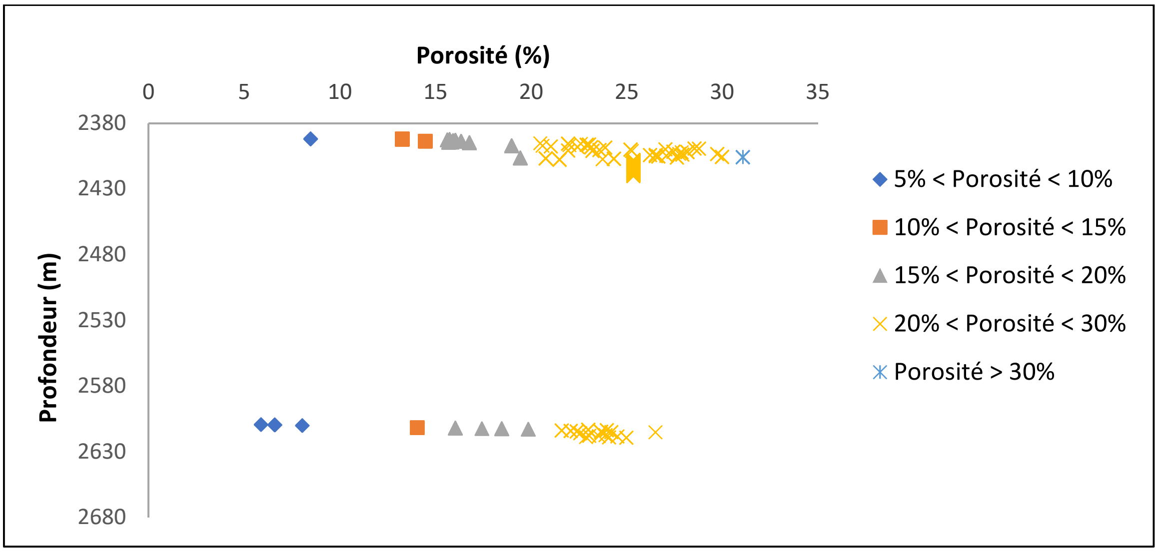

Fig. 7. Diagram of porosity variation versus depth in the FE-3 well

3.2 PETROGRAPHIC CHARACTERIZATION OF SANDSTONES

3.2.1 GENERAL APPEARANCE OF SANDSTONE TEXTURE

DETRITAL MINERALS

Quartz, more abundant, has angular to sub-rounded grains, monocrystalline (35 to 70%) of size 63µm (very fine) to 2mm (coarse) and polycrystalline (10 to 30%) of size varying from 63µm (very fine) at 2.9 mm (granule). The boundaries between the polycrystalline quartz grains are often intermeshed (Figs 8 A, B and 10 F). This characterizes quartz of metamorphic origin, unlike eruptive rocks that have straight boundaries (Figs 8 C and 10 F).

These limits often have several oxides essentially of pyrite (Fig 8 B). Some polycrystalline quartz grains sometimes show undulate extinctions, which indicates deformation of the mineral under stress (Fig 8 E). Quartz crystals also contain many fluid inclusions that appear as black points often concentrated along subparallel lines (Figs 8F and 9A, B) and also pyrite inclusions (Fig 8 D). Such quartz crystals are characteristic of low temperature crystallization. These grains also have dissolutions or corrosions at their border (Fig 8 E, C). The original grains surfaces are underlined by a thin band of growth (Fig. 9 C, D).

Feldspars, moderately abundant, are fine to coarse-grained, subangular to angular mainly represented by plagioclase (5 to 25%), microcline (2 to 15%) and orthose (about 2%). Plagioclase grains show two types of macle, probably Carlsbad (single macle) and albite (multiple macle). The cloudiness observed is due to zoned alteration of feldspar. The mineral formed by fine-grained alteration is sericite (Fig 9 E, F). Orthose alteration is revealed in polarized light (LPA) by a single Carlsbad macle (Fig. 10 A).

Micas, common, are elongated flakes and represented by muscovite (majority) at 5 to 15% and biotite (minority) at 3 to 5%. These flakes of micas often show a preferential alignment and sometimes altered into clay (Fig. 10 C), chlorite (Fig. 10 B, D) or calcite.

Rock fragments, angular to subangular grained, have a proportion of 2% to 10% but their proportion sometimes varies from 25% to 30% on some thin sections of the FE-1 well. Their characteristic flattened shape comes from the fragmentation of a cleaved source rock (Fig. 10 E).

Heavy minerals, very rare, are represented by tourmaline (Fig. 10 F).

AUTHIGÈNES MINERALS

These authigenic minerals are mainly represented by calcite, siderite, kaolinite and the presence of iron oxide (pyrite) (Fig. 11A, B, C, E).

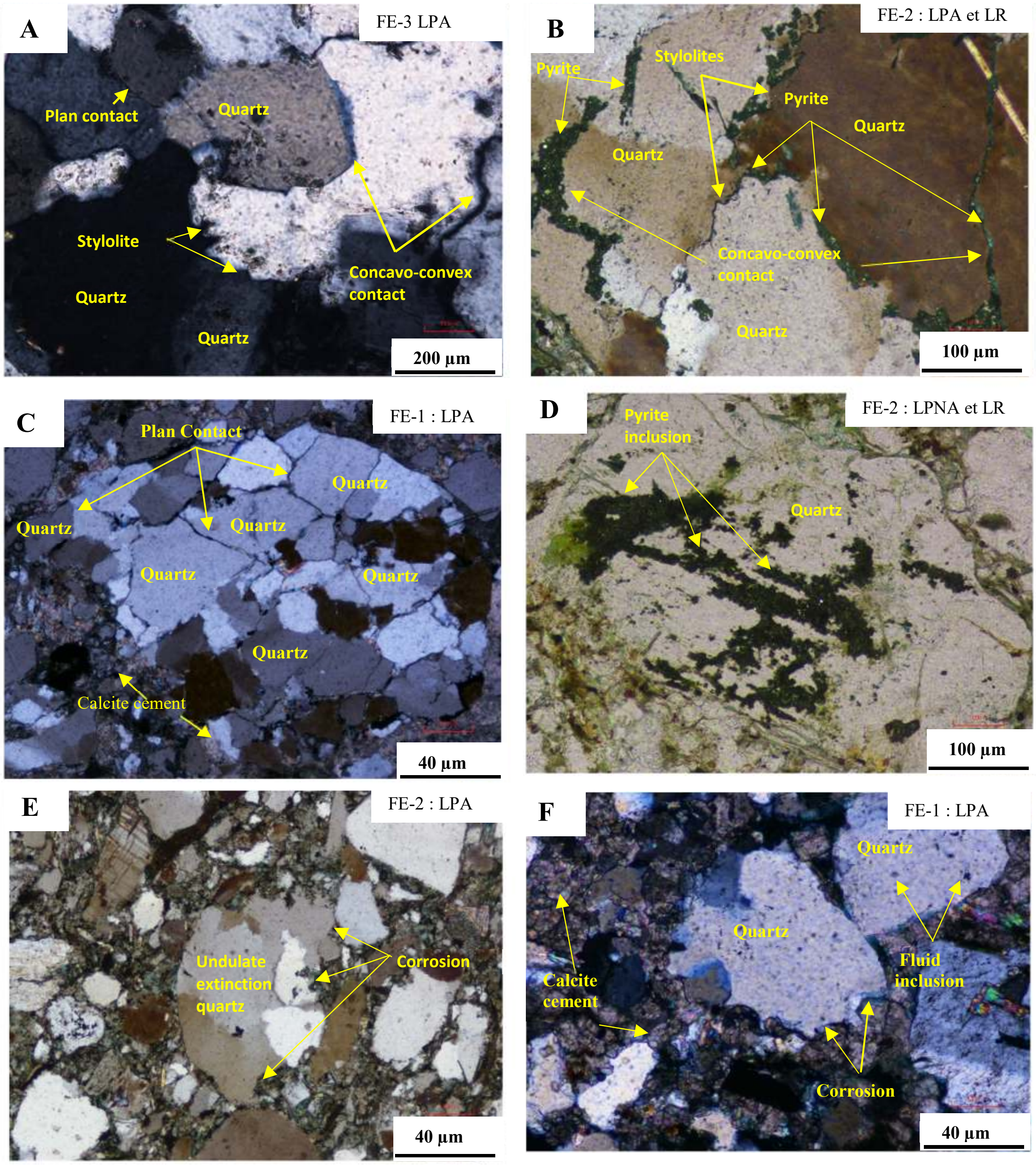

Fig. 8. Photomicrographs of sandstones of FE-1, FE-2, and FE-3 wells showing the enmeshed boundaries marked by the concavo-convex contacts and stylolite surfaces (A, B) and the straight boundaries shown by planar contacts (C). These limits contain iron oxides (pyrite). Corroded quartz grains with undulate extinction (E) and pyrite (D) and fluid (F) inclusions.

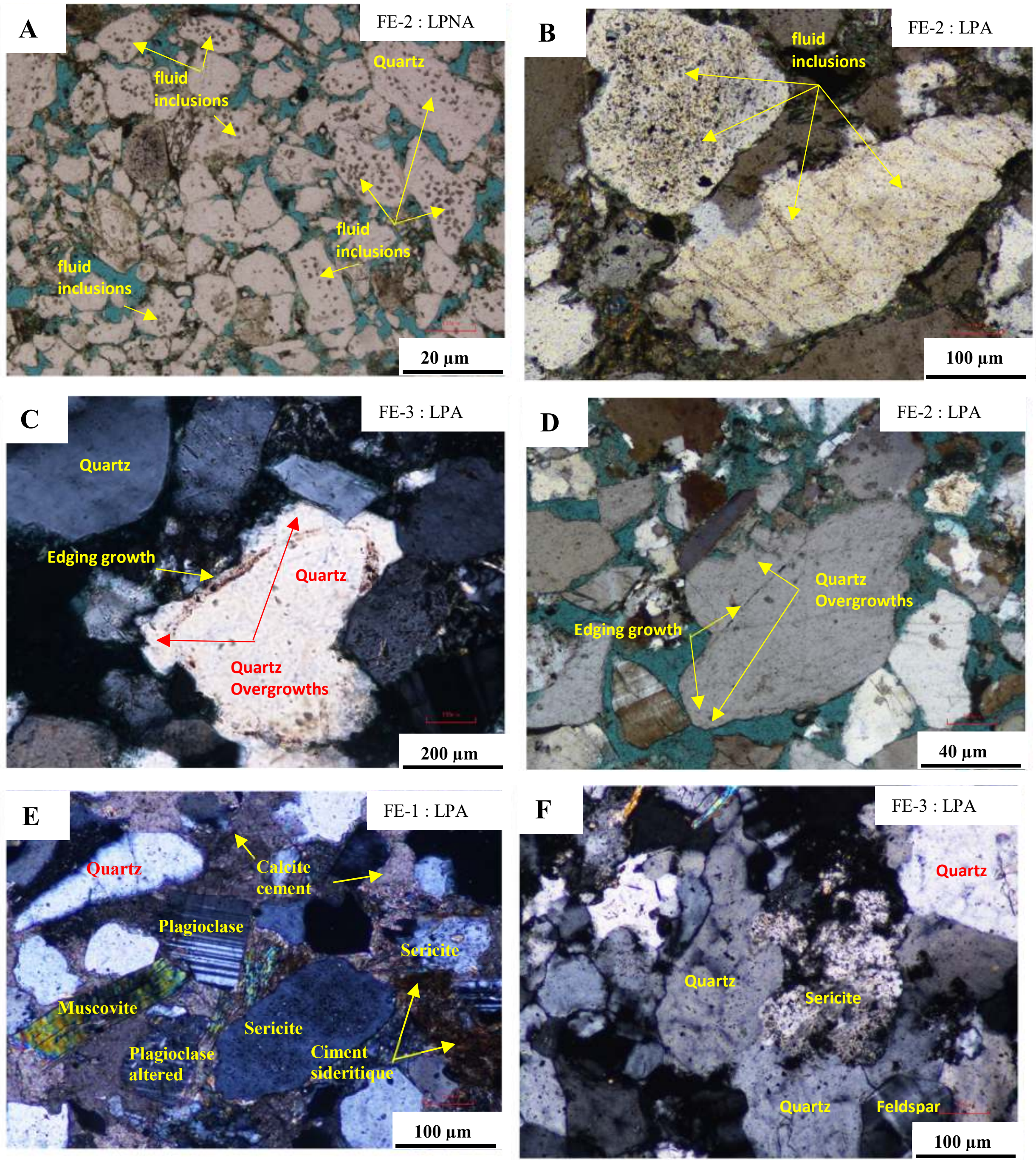

Fig. 9. Photomicrographs of detrital minerals from FE-1, FE-2, and FE-3 wells. Quartz with fluid inclusions (A, B) and overgrowths (C, D). The alteration of feldspar to sericite (E, F).

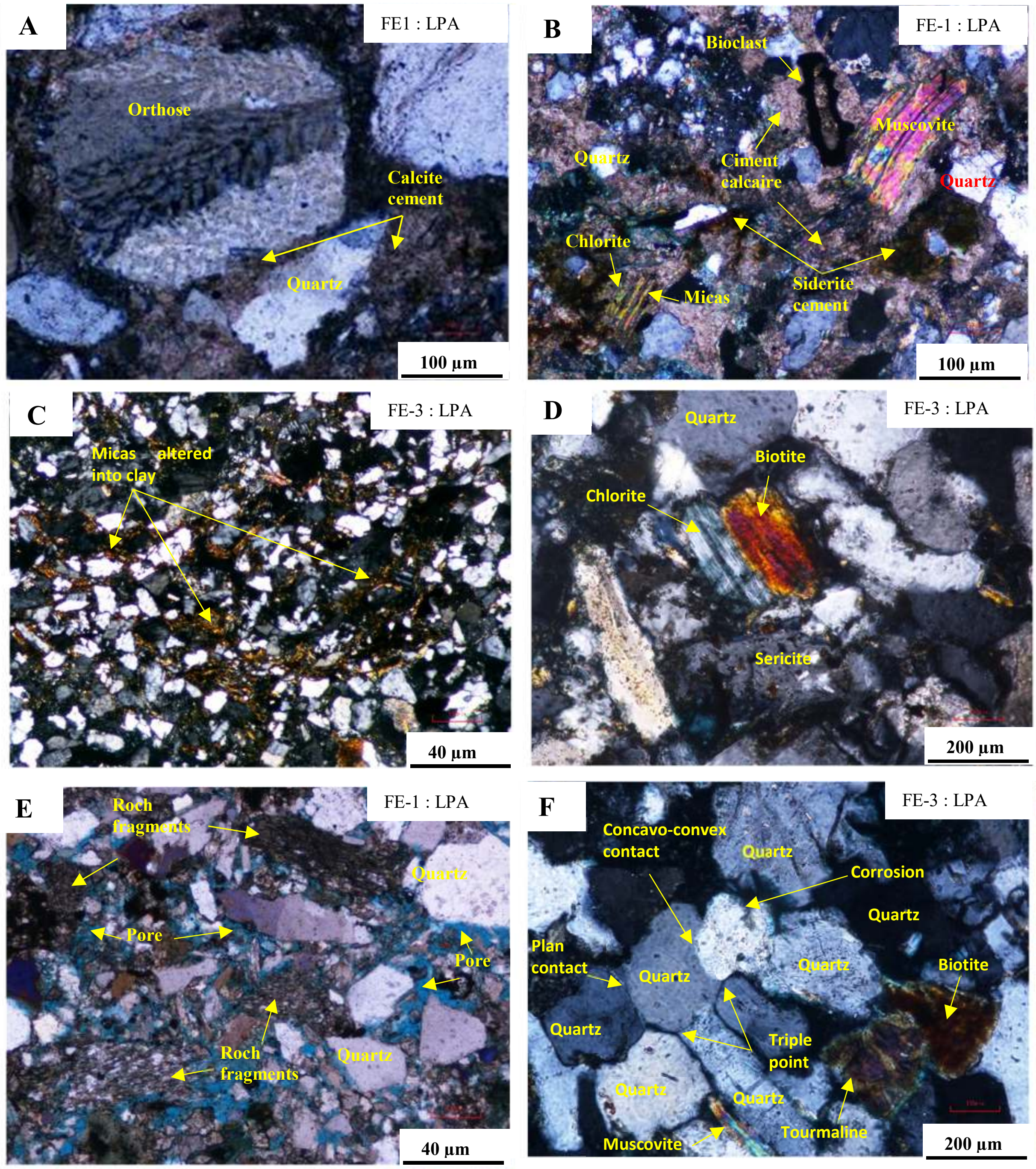

Fig. 10. Photomicrographs of detrital minerals from FE-1, FE-2, and FE-3 wells. Alteration of Orthosis marked by a single macle (A). Alteration of mica in chlorite (B, D) and clay (C). Flattened rock fragments (E), sandstones showing concavo-convex contact, plan contact and triple points (F). Tourmaline and biotite trapped between quartz grains (F).

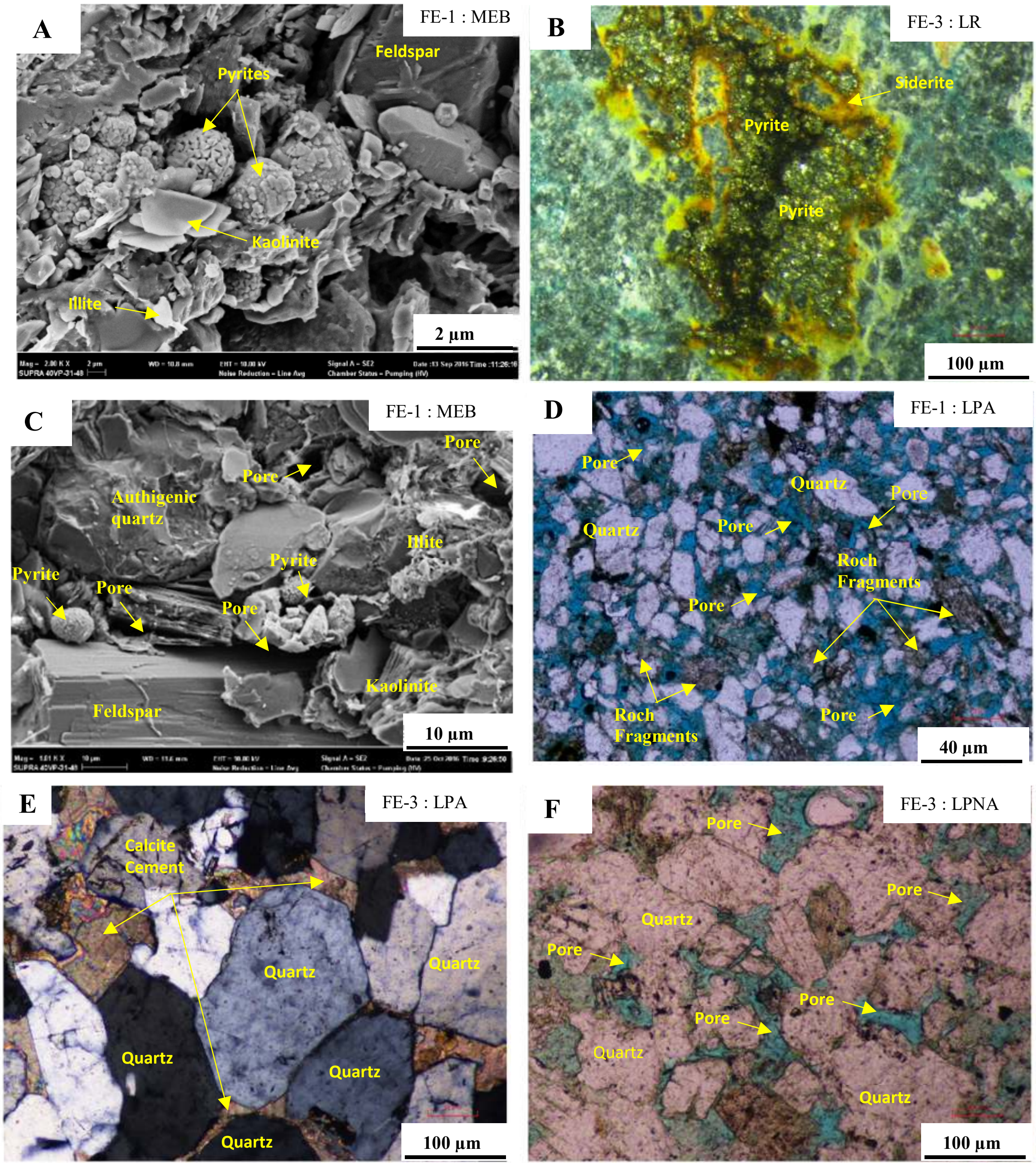

Fig. 11. Photomicrographs of authigenic minerals and pores from wells FE-1, FE-2, and FE-3. Presence of calcite (E), authigenic quartz (F), pyrite between the detrital minerals. Porosity blocked by calcareous cement (E), moderate (C, F) and good (D).

Porosity

Most of the pores on the thin sections are plugged with calcareous cement, suggesting poor porosity (Fig 11 C). Therefore, the reservoir is poor quality. Nevertheless, some thin sections have a medium porosity (Fig. 11 C, F) to good (Fig 11 B) interconnected (Fig 11 B), so a good reservoir.

3.2.2 Diagenesis

Compaction

The mechanical compaction is marked by the concavo-convex contacts, plane contacts, and triple points (Figs 8 A, B, C and 10 F). Mica (Figs. 9 E and 10 D, F) and heavy minerals such as tourmaline trapped between quartz grains (Fig. 10F) are also observed. Iron oxides such as pyrite are present at the boundaries between the polycrystalline quartz grains (Fig. 8 B).

Physico-chemical contacts are also well represented with dissolution surfaces. Pressure-dissolution results here in the presence of stylolites represented by sutures and gear surfaces (Figs 8 A, B and 12 A) and also accounts for the formation of quartz overgrowths (Figs 9 C, D). and 12 B)

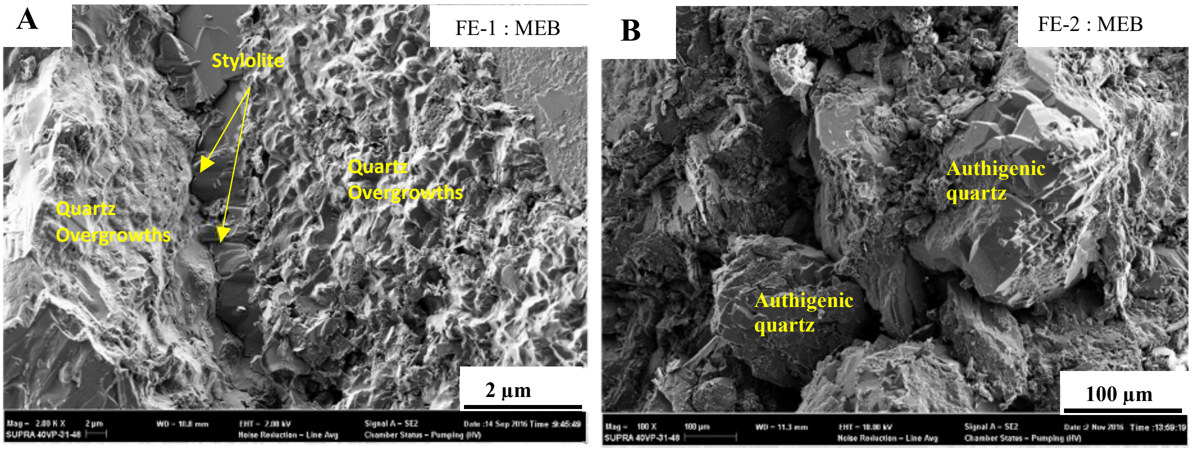

Fig. 12. ***Photomicrographs of sandstones of FE-1 and FE-2 wells showing dissolution pressure effects between quartz grains (A, B).***

Dissolution and recrystallization

Dissolution of feldspar grains and micas followed by precipitation of kaolinite and / or silica results in the creation of secondary porosity (Fig. 13 A, B, C, D). The phenomena of dissolution by corrosion of quartz grains are also observed characterizing a pronounced alteration during burying diagenesis (Fig 8 E, F). Silica overgrowths above the detrital quartz grains also mark the presence of silica resulting from the dissolution of feldspars and / or quartz (Fig. 9 C, D).

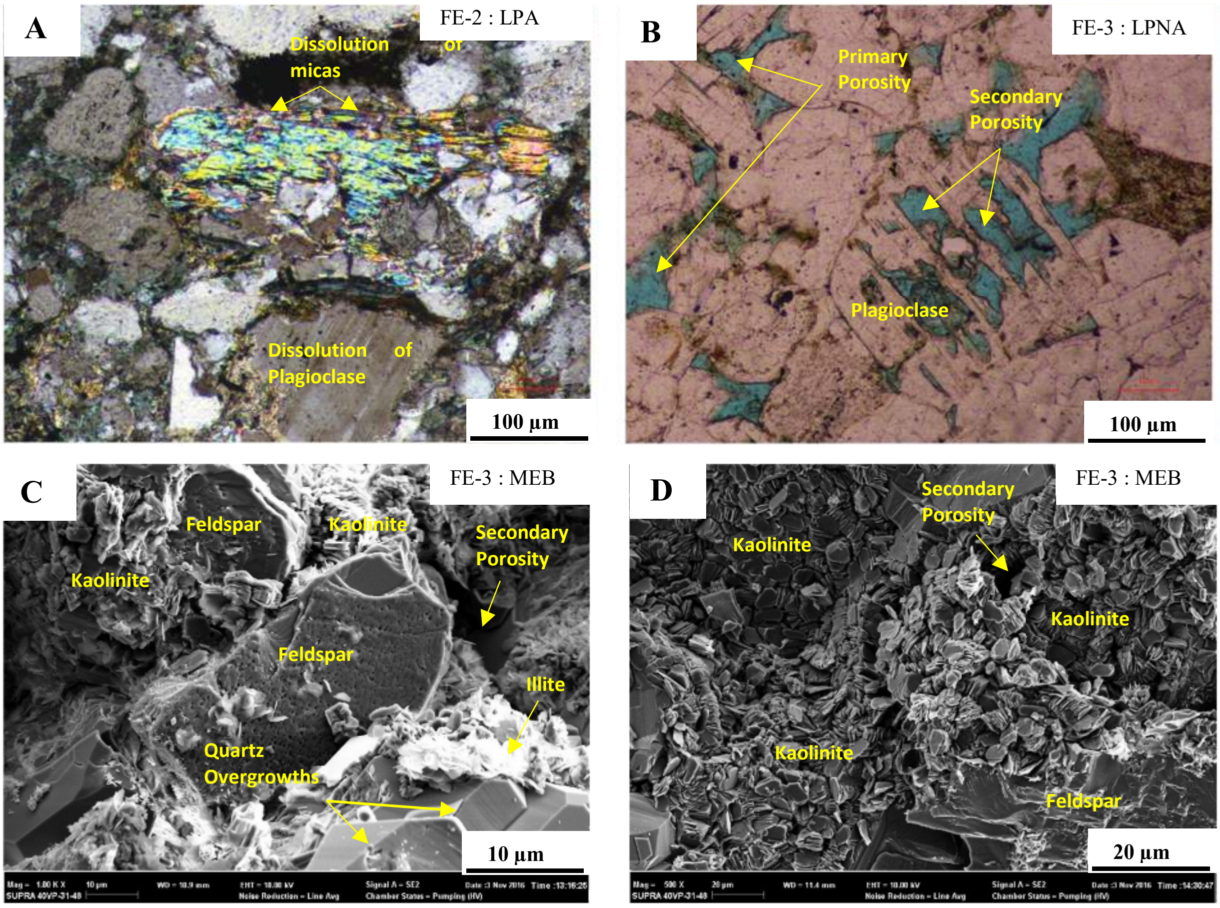

Fig. 13. Photomicrographs of sandstones of FE-2 and FE-3 wells showing secondary porosities due to dissolution of feldspar (B, C, D) and mica (A)

NEOFORMATION AND REPLACEMENT

The disappearance of feldspars and their replacement by clay minerals (kaolinite) is the most important neoformation diagenetic process observed on the studied thin sections (Figs 13 C, D and 14 A).

This process is characterized by relics partially or completely replaced by diagenetic clays. It is discreetly followed by a second clay phase which grows on kaolinite in this case illite (Figs 13 C and 14 A). The micas are sometimes altered, especially at their ends, to give kaolinite and / or illite (Fig. 14 B).

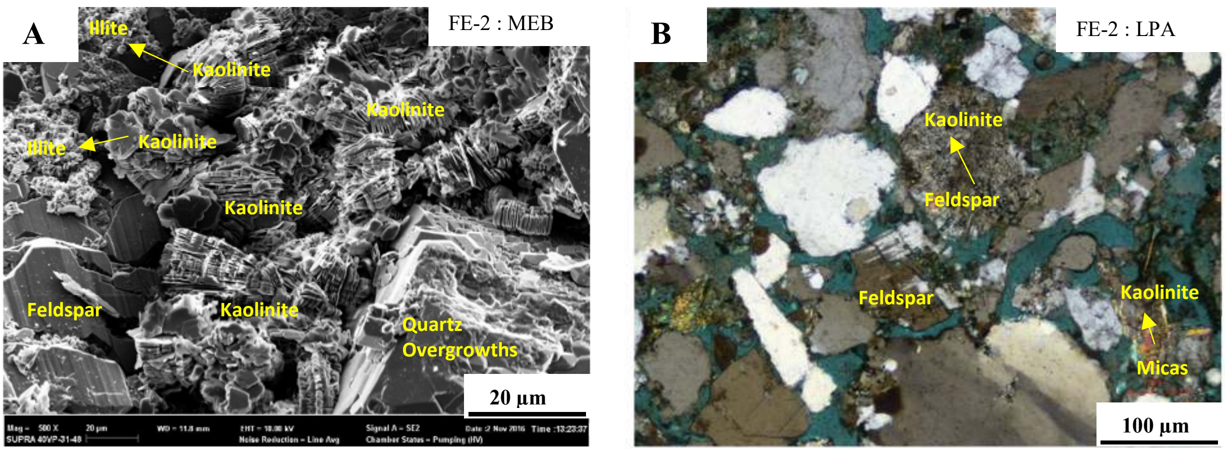

Fig. 14. Photomicrographs of sandstone of FE-2 well with kaolinite formation by alteration of feldspars (plagioclase) (A) and illitic phases growing above kaolinite (B).

CEMENTATION

Occlusion of the intergranular volume is observable on the analyzed thin sections by the presence of calcite, siderite and silica as cement around detrital particles (Figs 8 F, 9 E, 10 B, 11 E and 15 A). It can be seen that the cement takes on the exact shape of the grains which are otherwise compacted (Figs 11 E and 15 A). This mineral phase is also late.

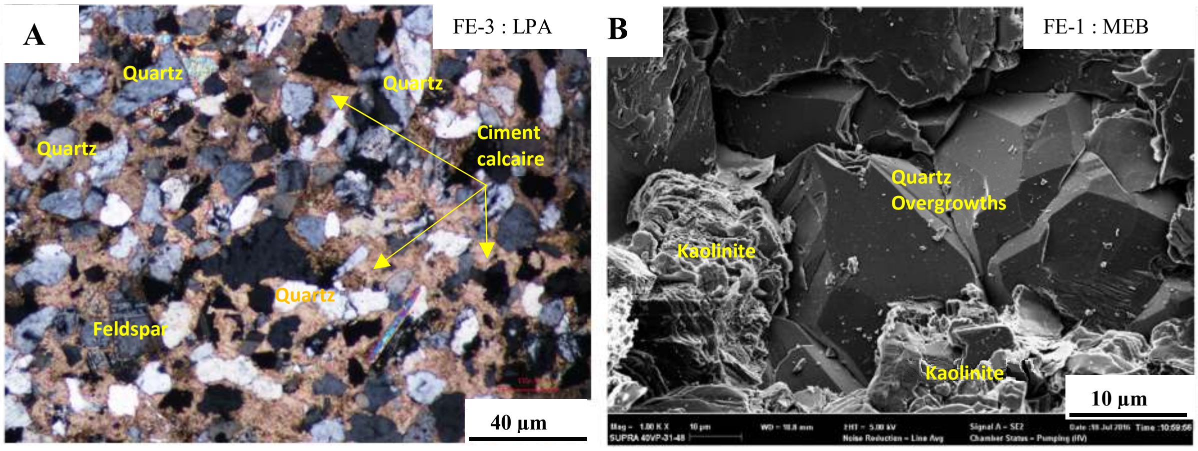

Fig. 15. Photomicrographs of sandstones of the FE-1 and FE-3 wells showing the presence of calcareous cement around the detrital grains (A) and the phenomenon of quartz overgrowth grains (B).

3.3 DIAGENETIC CONTROL ON PETROPHYSICAL PROPERTIES

3.3.1 INFLUENCE OF SILICIFICATION

Silicification is mainly present in the FE-3 well (around 10%) and weaklier in the FE-2 and FE-1 wells (<5%). Consequently, its influence on the degradation of the reservoir quality remains negligible in the FE-1 and FE-2 wells. Thin bands of growth around quartz grains reduce pore volume by occupying available space.

However, they usually retain some connectivity between the pores.

In addition, the finer edging growth of early or late quartz allow to solidify the sandstone and can then stop the compaction. This is a dual role to preserve a good quality of the reservoir. This influence is best observed in the FE-3 well, where the sandstones are arkosic and subarkosic arenites in which silicification is the most important diagenetic factor affecting porosity and permeability. In general, most of the silica in the sandstones of the various wells comes from stylolite.

3.3.2 INFLUENCE OF AUTHIGENIC CLAYS

Due to variations in the volume of authigenic clays and in proportion to clay corteges between the three fields, the influence of clays on the reservoir quality is heterogeneous. Indeed, each clays type causes different modifications in the intergranular pores depending on the morphology and the filling way of the crystals of kaolin, chlorite, and illite. Consequently, the permeability decreases correlatively as a function of the mineralogical composition of the dominant clay. The neoformed authigenic clays damage petrophysical properties, especially in sandstones of the FE-3 well, where permeability values are generally average (between 10 and 50 mD), low (between 1 and 10 mD) and negligible (<1 mD). But they do not much degrade those FE-1 and FE-2 wells which have excellent permeability.

3.3.3 INFLUENCE OF CARBONATED CEMENT

The influence of carbonate cement (limestone, siderite) on porosity and permeability is very high in FE-1 well sandstone compared to FE-2 and FE-3 wells. Occlusion of the intergranular volume is observable on the thin sections by the presence of calcite and siderite as cement around the detrital particles. Figures 11 E and 15 A show that the cement takes on the exact shape of the grains.

3.3.4 INFLUENCE OF MINOR DIAGENETIC PHENOMENA

Pyrite precipitation is not significant in terms of volume in FE-1, FE-2 and FE-3 sandstones. Its influence on porosity and permeability is negligible. In addition, the dissolution of feldspars as a diagenetic process creating secondary porosity leads to an increase in the volume of porosity. However, this type of porosity is expressed as isolated pores, and it does not lead to improved connectivity between pores and permeability. For this reason, the impact of feldspar dissolution on reservoir quality is generally low, and the difficulty of quantifying the exact volume of dissolution pores makes its role difficult to determine.

4 DISCUSSION

The porosity and permeability of the studied wells tend to decrease with depth, as for example in the North Sea Brent reservoirs (Ehrenberg, 1997) and the Gulf of Tertiary sandstones (Dutton and Loucks, 2010).

The diagenesis of cenomano-albian marine-deltaic sandstones from the ivorian sedimentary wells studied is comparable to those described in several basins around the world, such as the Westphalian C deltaic sandstones of the Kempen basin in Belgium (Long et al., 2009).), the Lower Cretaceous reservoir of the Nova Scotia Basin in Canada (Karim et al., 2010), the Gulf of Mexico Wilcox Reservoir (Dutton and Loucks 2010), and the South Palmyrid Basin Carboniferous (Wazir 2014).). In these basins a cementation of quartz, kaolinite, pyrite and siderite is dominant.

So, the diagenesis of shallow marine and deltaic hydrocarbon reservoirs is generally characterized by cementation of quartz, siderite, kaolinite, chlorite, and pyrite influenced by formation fluids that are associated with deposition environments marine rich in Fe, Mg and Ca and by the fluids produced because of the maturation of hydrocarbons.

For example, chlorite cement may be related to deltaic and / or fluvial deposition (Sullivan et al., 1999, Salem et al., 2005).

In addition, of the three studied wells in the ivorian sedimentary basin, only the FE-1 well shows an abundance of carbonate cement (66.67%). Alternations of limestone and albian sandstone were observed showing the influence of sequential stratigraphy on the cement source of carbonates in the FE-1 well.

The work of Tucker (1988) points out that the contact between the quartz grains passes flat contacts to stylolite according to the depth and make it possible to say that the sandstones of the three wells of the ivorian basin have experienced a considerable degree of compaction.

The dissolution of detrital feldspars is a very important diagenetic phenomenon since it creates secondary porosity (Schmidt and McDonald, 1979) but it also leads to the precipitation of neoformed clays (kaolinite or illite).

Generally, dissolution of feldspars occurs progressively during buryng (Milliken *et al.,* 1989, Glasmann 1992, Harris 1992, Wilkinson *et al.,* 2001). However, partially or totally preserved detrital feldspar grains are only present in the deepest sandstones of the ivorian sedimentary basin (FE-1> 2000 m, FE-2> 2500 m, FE-3> 2300 m) while pores rounded dissolution indicate a complete dissolution of the detrital feldspars in these sandstone reservoirs.

The presence of partially preserved detrital feldspar grains at significant depths has also been observed in other basins around the world, including the North Sea sandstone and Texas sandstone buried at more than 4000m (Wilkinson *et al.,* 2001). This indicates that the progression of feldspar dissolution in the study basins is related to the circulation of external acidic fluids.

These fluids rich in organic acids come from the source rocks to the upper parts of the reservoirs during the expulsion of hydrocarbons. These source rocks generate CO_2 during kerogen transformation (Hunt, 1995).

Pyrite and siderite precipitation in the sandstones of the studied wells is related to the deposition environment, in particular to a reducing environment during early diagenesis. This link with the depositional environment and the sedimentary facies has been demonstrated in several basins, such as the Statfjord Satellite reservoir in the North Sea (Ehrenberg, 1997) where a relationship between siderite and pyrite precipitation and micaceous sandstones has been highlighted.

The SEM mineralogical study revealed the presence of kaolinite, illite and chlorite in the pores of the various sandstone types. Kaolinites are mainly derived from feldspar alteration showing diagenetic origin (Ketzer *et al.,* 2003b). Illite develops on kaolinite. The illite formation that grows on kaolinite sheets occurs in deep diagenesis with temperatures between 100 and 130 ° C (Ehrenberg and Nado, 1989; Mc Aulay *et al.,* 1993, 1994). This transformation takes place at a depth of about 3500 m ((Ehrenberg and Nado 1989, Bjorlykke *et al.,* 1992).

As we can see, several studies highlight the control of diagenesis on the petrophysical properties of sandstones.

These diagenetic processes are mainly represented by mechanical compaction in shallow reservoirs (Berner 1980, Palmer and Barton 1987, McBride et al., 1989, Lundegard 1992, Wilson and Stanton 1994, Dutton and Loucks 2010). In contrast, these phenomena are chemical in muddy sandstones and occur at significant depths (Houseknecht 1984, Dewers and Ortholeva 1991, Ramm 1992, Angevine and Turcotte 1993, Bjørkum *et al.,* 1993, Ramm and Bjørlykke 1994; Lemée and Gueguen, 1996) and quartz cementation (Heald, 1955, Walderhaug, 1994, Worden and Morad, 2000, He *et al.,* 2002, Dutton and Loucks, 2010).

These diagenetic processes are responsible for the destruction of porosity and permeability in some sandstones (Houseknecht 1987, Wilson and McBride 1988, Lundegard 1992, Marfil *et al.,* 1996, Worden and Morad 2000, Girard *et al.,* 2002, Worden and Burley 2003, Chester *et al.,* 2004, Cook *et al.,* 2011).

The impact of compaction is greater on porosity reduction than quartz cementation because of its dual role: by reducing porosity and by forming a silica source that precipitates into adjacent intergranular pores (McBride, 1989; Bjørlykke and Egeberg, 1993).

5 Conclusion

Direct petrophysical measurements on sandstone samples generally showed decreases in permeability and porosity versus depth.

Sedimentary petrography on these samples revealed three types of sandstone (subarkosic, arkotic and lithic arenites) in the studied wells.

In these sandstones, the mechanical and chemical compaction, the cementation of carbonates and quartz are the most influential diagenetic processes on the petrophysical properties despite the heterogeneity of their distribution and their importance in the Ivory Coast basin.

Petrography has thus made it possible to estimate the degree of compaction by analyzing the contacts between the different detrital quartz grains in these three wells studied. It was therefore possible to identify planar, concavo-convex, meshed, sutured (stylolithic) contacts and triple points.

A virtual chronology of the diagenetic events occurring in the sandstones of the wells studied in the ivorian sedimentary basin was proposed as follows:

- mechanical and mechano-chemical compaction (planar, concavo-convex and stylolithic contacts),
- dissolution of low stability grains (feldspars and micas) followed by
- neoformation (kaolinite, illite),
- the quartz grains that have remained in contact have begun to undergo pressure-dissolution phenomena by releasing the silica,
- cementation by calcite, silica, iron,
- this remobilized silica enlarges the detrital quartz grains by feeding (overgrowths),
- diagenesis of exhumation marked by the phenomena of meteoric alteration.

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