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Classification and Diagenetic Characteristics of the Cretaceous Sandstones in the Southern Bredasdorp Basin, Offshore South Africa

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Abstract: A systematic petrographic and geochemical studies of 92 representative sandstone samples from exploration wells E-AH1, E-AJ1, E-BA1, E-BB1 and E-D3 in the southern part of the Bredasdorp Basin was undertaken to classify the sandstones as well as unravel the main diagenetic processes and their time relations. Petrographic study shows that the sandstones are largely subarkosic arenite and arkosic litharenite, which have underwent series of diagenetic processes as a result burial, rifting and subsequent uplift. The main diagenetic processes that have affected the reservoir properties of the sandstones are cementation by authigenic clay, carbonate and silica, growth of authigenic glauconite, dissolution of minerals and load compaction. The major diagenetic processes reducing the porosity are calcite cementation in the subarkosic arenite, and compaction and quartz cementation in arkosic litharenite. On the other hand, the formation of secondary porosity due to the partial to complete dissolution of early calcite cement, feldspars and minor grain fracturing has improved the reservoir property of the sandstone to some extent. The clay minerals in the sandstones commonly acts as pore choking cement, which reduces porosity. In general, there is no particular diagenetic process that exclusively controls the type or form of porosity evolution in the sandstones.

Key words: diagenesis, cementation, reservoir properties, sandstones, Bredasdorp Basin

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1 Introduction

Early exploration for hydrocarbon reservoirs was originally centred on the acquisition of knowledge on the regional tectonic setting of the host basin, followed by thorough assessment of local geology and stratigraphy. Nonetheless, recent research findings have shown that the search for reservoir properties in sandstone necessitates extra attention on diagenesis. Remote sensing and geophysical methods are used in petroleum exploration for identifying the presence of sandstones. However, they do not give any information or help to locate sandstones that have been preserved from major diagenetic changes. Hence, it is very crucial to have a thorough understanding of the factors controlling reservoir quality so as to assist with the appraisal of the economic feasibility of petroleum discoveries. Once petroleum has been discovered in a basin, it is very essential to have a detailed understanding of the diagenetic characteristics and evolution of the reservior rock for the prediction of their quality as hydrocarbon reservoirs as well as assist in future exploration and appraisal efforts (Selley, 1997; Taylor et al., 2010).

Several researchers including Bloch et al. (2002), Burley and Worden (2003), Mackenzie (2005) and Milliken (2006) and Baiyegunhi et al. (2017) have reported that diagenetic changes or modifications in clastic rocks have a momentous impact on reservoir quality by altering their original porosity and permeability. Thin sections petrographic study is a very crucial and important tool used for investigating the types, timing and rate at which the diagenetic processes have affected porosity and permeability of clastic rocks (Ajdukiewicz and Lander, 2010). The link or connection between diagenesis and reservoir quality have been reported by Roswell and De Swart (1976), Reed et al. (2005), Macquaker et al. (2014), Baiyegunhi et al. (2017) and Chima et al. (2018). However, the main factors influencing diagenesis are still not well understood and diagenetic modifications in reservoir properties is still unpredictable (Molenaar, 1998). Diagenesis is generally defined as the sum of physical, chemical, and biological/biochemical changes that sediments pass through or undergo from the time of deposition until just before the transition to metamorphism. These changes occurred due to several factors that includes cementation, authigenesis, bacterial actions, replacement, recrystallization, dissolution, and compaction. The economic importance of certain sandstone units as a source or reservoir rock for petroleum may solely depend on the diagenetic history of the units as

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well as their original depositional characteristics (Burley and Worden, 2003; Boggs, 2009). Diagenetic processes are incessantly active as the ambient environment changes in regards to temperature, pressure and pore fluid chemistry during deposition, burial and uplift cycle of the basin history (Burley and Worden, 2003). These processes are alleged to occur above the zone of metamorphism with temperatures below about 195°C–220°C and at pressures $\leq$ 5 kb (Boggs, 2009).

The Bredasdorp Basin covers the greater part of the larger Outeniqua Basin representing a productive petroleum bearing basin, off the south coast of South Africa (Fig. 1). The efficient exploitation of the sandstone reservoirs of the Bredasdorp Basin depends on a number of factors that include understanding of the diagenetic features and evolution history. However, up to date, only a few unpublished work exist on the diagenesis of the Cretaceous sandstones of the Bredasdorp Basin. The aim of this study is to classify the Bredasdorp sandstones as well as account for the diagenetic characteristics of the sandstones. In general, sediments are affected by diagenetic processes (i.e. cementation, mineral replacement and recrysllization) after deposition, which are all modifying the original composition of the sediments. Also, we investigate if diagenesis has meaningfully influenced the original or initial petrologic composition of the sandstones after deposition. By so doing, this research work will add new information on diagenetic processes, diagenetic stages and their paragenetic sequence.

2 Geological Setting

The Bredasdorp Basin is a south-easterly trending rift basin that is characterized by half-graben structures. These half-grabens are mostly made up of the Upper Jurassic, Lower Cretaceous, Cretaceous and Cenozoic rift to drift strata. The basin developed along with other sub-basins of the larger Outeniqua Basin, as a result of rift and drift activity during the break-up of Gondwana supercontinent along the Agulhas–Falkland Fracture Zone (PASA, 2012; Fig. 1). The Bredasdorp Basin which is located off the south coast of South Africa (southeast of Cape Town and west–southwest of Port Elizabeth), containing mainly sandstones with subordinate mudrocks. The basin is about 80 km wide and 0.2 km long (Broad et al., 2006) and the western and eastern sides are bounded by the Columbine–Agulhas Arch (CAA) and the Infanta Arch (IA), respectively (Brown et al., 1995). The CAA and IA are extended basement highs and they are made up of the Cape Supergroup granite and Precambrian (basement) metamorphic rocks.

The Bredasdorp Basin was reported to have developed along the South African continental margin, underneath the Indian Ocean due to extensional episodes during the initial stage of rifting in the Late Jurassic–Early Cretaceous (Burden and Davies, 1997). As reported by Akinlua et al. (2015), the basin underwent a successions of structural distortion during the break-up of Gondwanaland as well as the continents that falls within the southern hemisphere. According to Tinker et al. (2008), the dextral trans-tensional stress or right-lateral shear movement that was produced along the Falkland–Agulhas Fracture Zone (AFFZ) occurred as a result of the separation of the Falkland Plateau from the Mozambique Ridge as well as the break-up of west Gondwana. The tectonic events initiated the development of normal faulting north of the AFFZ, resulting in the creation of graben and half-graben sub-basins (i.e. Bredasdorp Basin) (Brown et al., 1995). The basin is principally filled-up with the late Jurassic and early Cretaceous syn-rift continental and marine sediments as well as the post Cretaceous and Cenozoic divergent rocks, mostly comprising of slanting or inclined half-graben structures.

Stratigraphically, the basin is made up of Oxfordian–Recent stratigraphic column (Brown et al., 1995; PASA,

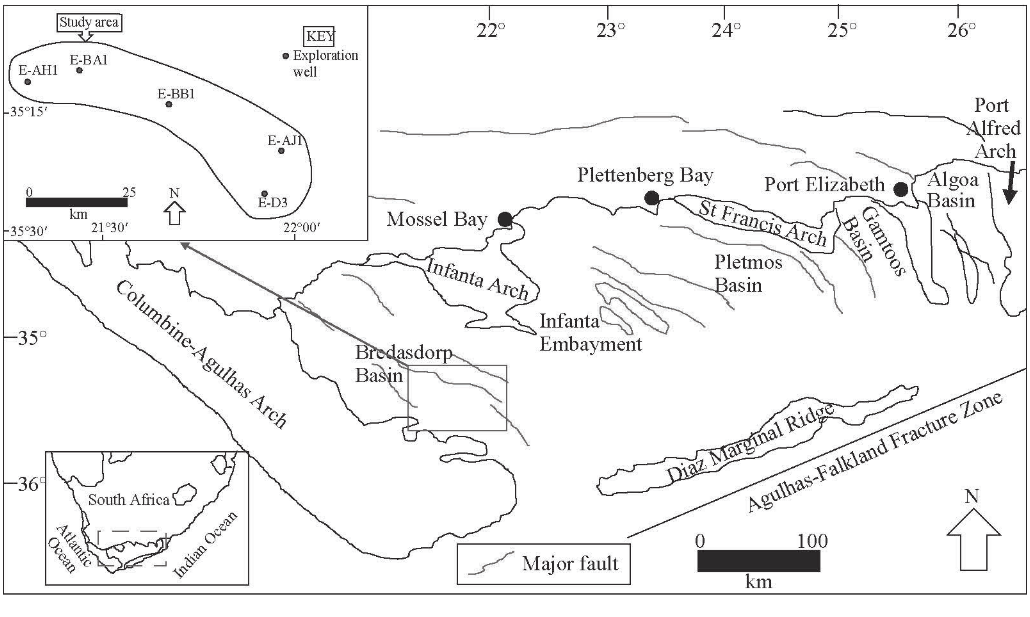

Fig. 1. Map of the study area showing distribution of the exploration wells across the Bredasdorp Basin (modified from Burden and Davies, 1997).

2012) overlying the Cape Supergroup (McMillan et al., 1997). The stratigraphic column shows the occurrence of a syn-rift phase and post-rift or drift phase (Jungslager, 1996). The syn-rift phase can be subdivided into the syn-rift I and syn-rift II sedimentation (Jungslager, 1996). The syn-rift I sedimentation took place from the middle Jurassic up to the late Valanginian (Basement to 1At1) whereas the syn-rift II sedimentation occurred from the late Valanginian until the Hauterivian (1At1 to 6At1) (PASA, 2012; Fig. 2). The syn-rift I succession is terminated by a regional 1At1 unconformity, signifying the beginning of a renewed rifting (synrift II) phase initiated due to early movement along the AFFZ at approximately 121 Ma (Valanginian–Hauterivian boundary) (Jungslager, 1996). The syn-rift II was later followed by the Transitional (Early Drift) phase, which occurred during Hauterivian–Early Aptian (6At1 to 13At1) (Fig. 2). The Transitional (Early Drift) phase was characterised by recurrent episodes of progradation and aggradation and it was mostly affected by tectonic events and eustatic sea-level changes (Broad et al., 2006). This phase was considered as the first deep water deposits in the Bredasdorp Basin and they were deposited due to major subsidence of the basin as well as the increase of water depth. On the other hand, the late drift phase trailed a major marine regression in the Bredasdorp Basin during the early Aptian. This regression event resulted in a major erosion which is marked by the 13At1 unconformity. The erosion period is followed by a marine transgression, which carried and deposits organic-rich claystone in the basin under an anoxic condition (McMillan et al., 1997). The onset of the late drift-phase is manifested or noted by the 14At1 mid-Albian unconformity (Fig. 2), which marks the beginning of the active thermally driven subsidence when the Columbine–Agulhas Arch was cleared by the trailing edge of the Falkland Plateau in the Late Albian (PGS, 1999; Broad et al., 2006).

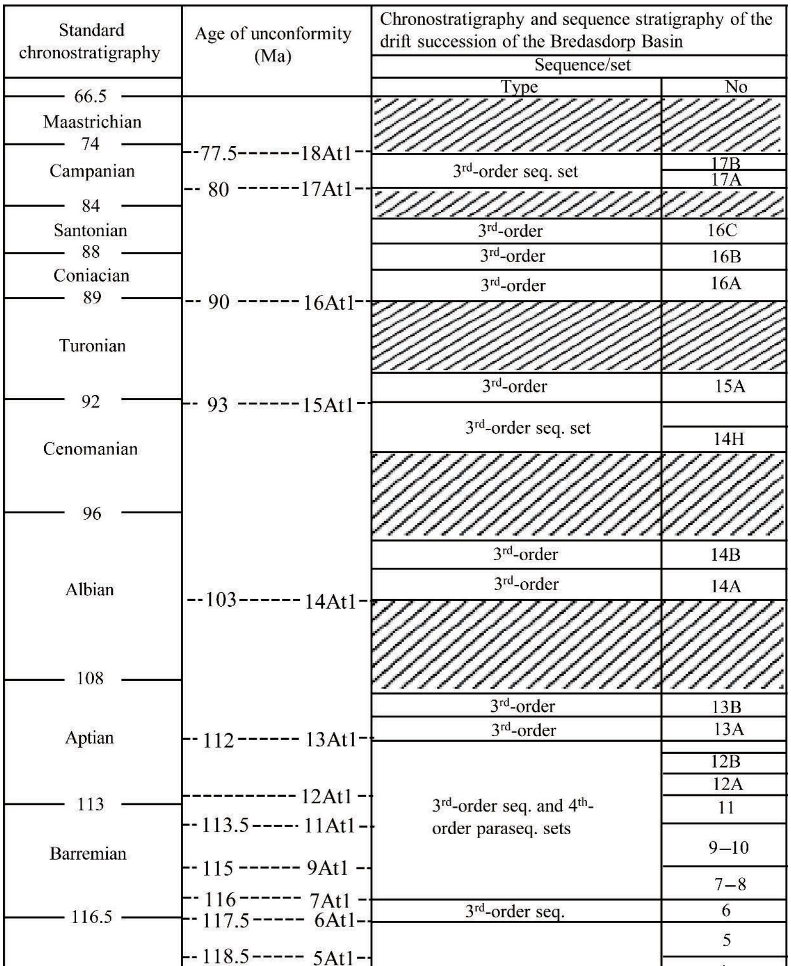

Fig. 2. Summary of sequence nomenclature and chronostratigraphy of the drift succession in the Bredasdorp Basin (Brown et al., 1995).

3 Materials and Methods

A total of 150 thin sections of the 92 representative sandstone samples collected from exploration wells E-AH1, E-AJ1, E-BA1, E-BB1 and E-D3 (Fig. 1; Table 1) were studied under optical microscope to determine their mineralogical compositions, textural characteristics and cement types. Furthermore, 50 out of the 92 sandstone samples were cleaned, glued on a glass microscope slide and gold coated using Cressington Gold Coater 108 Gold/A machine. The coated samples were analysed using a scanning electron microscopy (SEM) instrument (Model: JEOL JSM-6390LV) fitted with an energy dispersive x-ray microanalyser (EDX). The samples were observed in backscattered electron (BSE) and secondary electron imaging (SEI) modes of imaging. The petrographic microscopy and modal composition analysis were carried out at the Petroleum Agency of South Africa in Cape Town, while the SEM and EDX analyses were performed at the University of Fort Hare, South Africa. The cement types, textures, primary and authigenic minerals of the sandstones were described based on petrographic study of thin sections, SEM and EDX analyses. Furthermore, clay minerals, quartz overgrowth, diagenetic textures, dissolution effect and other related diagenetic imprints were examined using SEM. For the modal composition analysis, at least 500 points were counted per thin section using the procedures recommended by Dickinson and Suczek (1979) and Dickinson et al. (1983). An Olympus BX51 microscope fitted with an Olympus DP72 digital camera was used to analyse each of the thin sections in accordance with the Gazzi-Dickinson's point-counting technique. For each thin section, an evenly spaced counting grid was deployed to go across the thin section, and the framework grains as well as the matrix were counted under the grid nodes. The grids were equally spaced such that each grid go beyond the grain size in order to avoid counting grain more than once. The framework components were determined using the proposed methods of Dickinson and Suczek (1979), Dickinson et al. (1983) and Dickinson (1985). The constituent minerals of the sandstones of the Bredasdorp Basin were categorized into quartz (monocrystalline and polycrystalline), feldspar, lithic fragments, mica, cement and matrix. The amount of pore spaces were also accounted for during point counting. In addition, 30 sandstone samples were also analysed by X-ray diffraction (XRD) to determine the mineral compositions. The XRD analysis was carried out using the backloading preparation method. The diffractograms were obtained by means of a Malvern Panalytical Aeris diffractometer with PIXcel detector and fixed slits with Fe filtered Co-Kα radiation. The phases were identified using X'Pert Highscore plus software while the relative phase amounts (weight%) were estimated using the Rietveld method.

4 Results and Discussion

4.1 Modal composition

The grain sizes and sorting of the Bredasdorp sandstones are fine to medium grained and moderately sorted to moderately well sorted, respectively. The sandstones are made up of framework grains, accessory minerals, matrix, cement and pores. The framework minerals are quartz, feldspar, lithic fragments and glauconite, while the accessory minerals are mica (biotite and muscovite), zircon, and rutile. The quartz grains are usually subangular to rounded in shape and constitute about 52.2–68.0% of the framework grains (Supp. Table 1). The quartz occurs as both monocrystalline quartz (Qm) and polycrystalline quartz (Qp) grains and often exhibits undulose and planar extinctions. The monocrystalline quartz (Qm) dominates, comprising of about 97.04% of the total quartz grains in the sandstones. The feldspar grains often range from subangular to subrounded shape and constitute nearly 10.0–18.0% of the framework grains. The observed feldspar types are alkali feldspar (orthoclase and microcline) and plagioclase feldspar (albite), with orthoclase being the most dominant mineral. Quantitatively, only about 24% of the alkali feldspar (mainly orthoclase with few microcline grains) shows twinning, whereas approximately 76% of the plagioclase seems to be untwinned. The lithic fragments constitute about 5.0–10.2%, averaging 7.8% of the framework grains. These lithic fragments often occur as fine quartz grains in clay matrix (sedimentary lithic fragment) and clasts of sutured grains with no matrix (metamorphic lithic fragment). The sedimentary lithic fragments (fragments of sandstone and mudrock) constitute a larger percentage of the total lithic fragments. The matrix and cement serves as binding materials around the framework grains. The matrix constitute about 3.2–13.8%, whereas the cement constitute between 1.8–10.0% of the overall composition. The matrix is typically clay minerals and they are either detrital or formed diagenetically. The diagenetic matrix minerals are thought to have been formed due to the alteration and precipitation of the framework grains, in addition to the recrystallization of other matrix minerals. Likewise, the XRD analysis shows that the most abundant minerals include quartz (56.0–73.7%) and plagioclase (6.1–14.5%), while the dominant clay mineral is kaolinite (1.6–13.6%) (Supp. Table 2). The observed clay minerals are kaolinite, illite, smectite and chlorite.

Table 1 Locations and total drilling depth of the studied exploration wells

Wells/borehole	**E-AH1**	**E-AJ1**	**E-BA1**	**E-BB1**	**E-D3**
Co-ordinates	Latitude 35°11′13.40″S Longitude 21°08′37.07″E	Latitude 35°20′09.15″S Longitude 21°58′37.45″E	Latitude 35°09′29.67″S Longitude 21°28′31.19″E	Latitude 35°14′51.32″S Longitude 21°41′41.088″E	Latitude 35°28′45.91″S Longitude 21°56′16.16″E
Kelly Bushing (KB) to sea level (m)	26	26	22	22	18
Water depth (m)	91	142	115	122	156
Total drilling depth (m)	3729	3490	3130	3320	3996
No. of samples	8	27	11	38	8

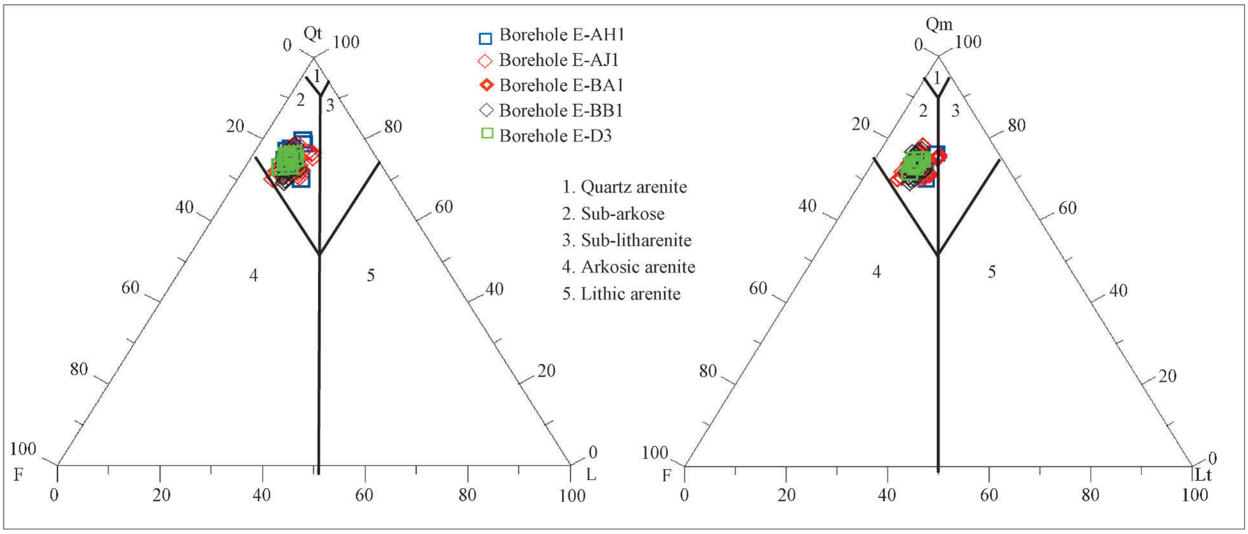

Fig. 3. Sandstone modal data plot of the total quartz-feldspar-lithic fragments (Qt-F-L) and monocrystalline quartz-feldspar-total lithic fragments (Qm-F-Lt) on the background ternary diagram of Dott (1964).

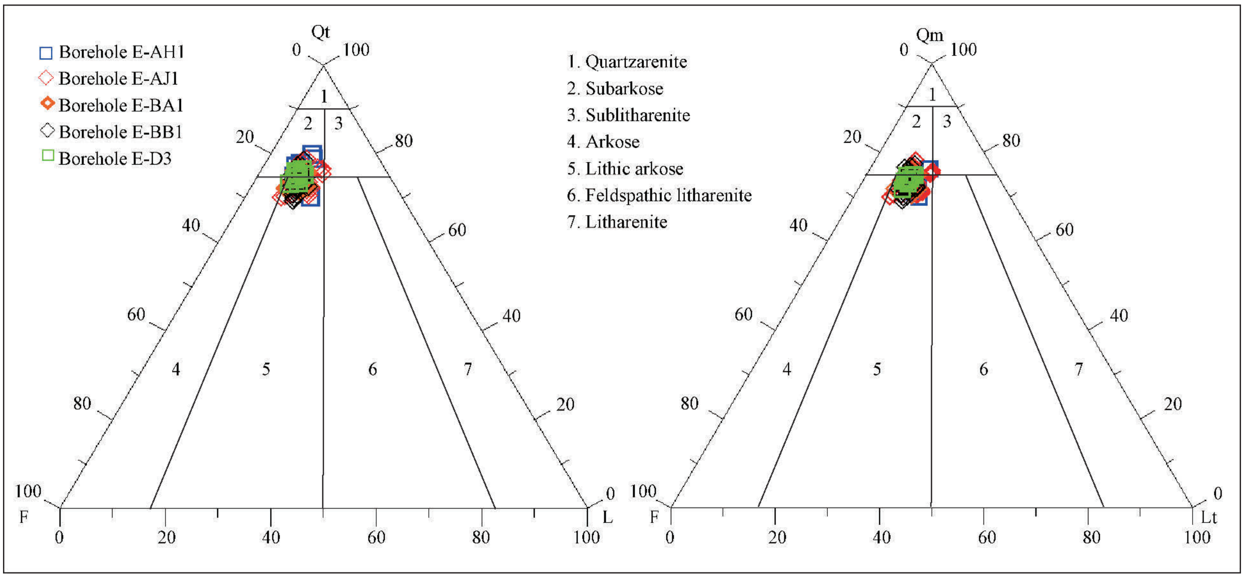

Fig. 4. Sandstone modal data plot of the total quartz-feldspar-lithic fragments (Qt-F-L) and monocrystalline quartz-feldspar-total lithic fragments (Qm-F-Lt) on the background ternary diagram of Folk (1974).

4.2 Sandstone classification

The most widely used and effective methods for classifying sandstones combines the textural criteria (i.e. proportion of the matrix) with the compositional criteria (i.e. percentages of the framework grains) (Dott, 1964; Pettijohn et al., 1972, 1973; Folk, 1974; Dickinson et al., 1983). In this study, the classification of the Bredasdorp sandstones is based on the classification schemes proposed by Dott (1964) and Folk (1974). These schemes are based on the percentages of the framework grains (quartz, feldspar and lithic fragments) in a triangular plot such that these three components serves as the end members to form a Q-F-L ternary diagram. The classification method of Dott’s (1964) method shows that the sandstones could be classified as subarkosic arenite (Fig. 3), whereas the Folk's (1974) scheme revealed that the sandstones are subarkosic arenite and arkosic litharenite (Fig. 4).

4.3 Diagenesis of the Bredasdorp sandstones

The primary diagenetic processes that have sturdily affected the Bredasdorp sandstones are cementation and compaction, as well as the dissolution, replacement and recrystallization of minerals.

4.3.1 Cementation

Cementation is the diagenetic process whereby authigenic minerals grow or precipitated around grains and in the pore spaces of sediments which thereby binds the detrital grains together. The cements that binds the framework grains of the Bredasdorp sandstones are mainly carbonate (calcite), glauconite, silica (quartz), sulphide (pyrite) and authigenic clay (kaolinite and smectite) cements.

4.3.1.1 Carbonate cementation

Carbonate cements are one of the dominant authigenic minerals in the Bredasdorp sandstones. The observed carbonate cement in the sandstones is calcite cement. This cement precipitates in the intergranular pores and is often seen to have replaced detrital quartz and feldspar. Carbonate cement usually occur at a later stage of diagenesis when burial had increased to the point where formation waters had become more alkaline. Calcite cementation is a common type of cement in the Bredasdorp sandstones and it is present in the five studied boreholes. This cement occurs as ferroan and non-ferroan calcite (Fig. 5), with the non-ferroan calcite being the most dominant type of the carbonate cements. The ferroan calcite cement is observed as scattered patchy crystals and as isolated pore fillings. Ocassionally, the ferroan calcite cement fills both the primary and secondary intergranular pores. On the other hand, the non-ferroan calcite cements occurs as poikilotopic pore-filling crystals, which generally fills in the primary pores and replaces feldspar and quartz grains (Fig. 5). The ferroan calcite are often seen in association with detrital carbonate components, which possibly shows that the ferroan calcite acted as nuclei for cement formation. These ferroan carbonate cement is alleged to have existed under reducing alkaline pore water conditions and the ions required for the formation of the cement were probably sourced from alumino-silicate grain dissolutions and clay mineral transformations. Also, the ferroan calcite cement might have survived dolomitization as a result of poor permeability for the circulation of Mg-rich fluids. Generally, most of the matrix (clay minerals) and detrital grains were partially replaced by calcite and in few instances, the replacement entered into the centres of quartz and feldspar grains.

4.3.1.2 Glauconite cementation

The glauconite cement is a common cement type in the Bredasdorp sandstones and it is visible as greenish colour (Fig. 6). It directly precipitates in the intergranular pore space, line on the grain surfaces and fractures or cracks. Quantitatively, the glauconite cement range from about 0.4–3.6%, averaging 2.1% of the overall composition. The occurence of these glauconitic minerals as rims on grain surfaces or growth of the mineral by partly or completely replacement of different detrital grains such as K-feldspar grains, suggest their possible authigenic growth. The initial process of glauconitization of the detrital K-feldspars is seen in the form of small blebs along the grain boundaries, cleavage planes, and fractures until the feldspar is completely replaced. Generally, the authigenic glauconite grains are mostly formed as a result of glauconitization/ replacement of feldspars, muscovite, and clay minerals. These glauconites have light green colour

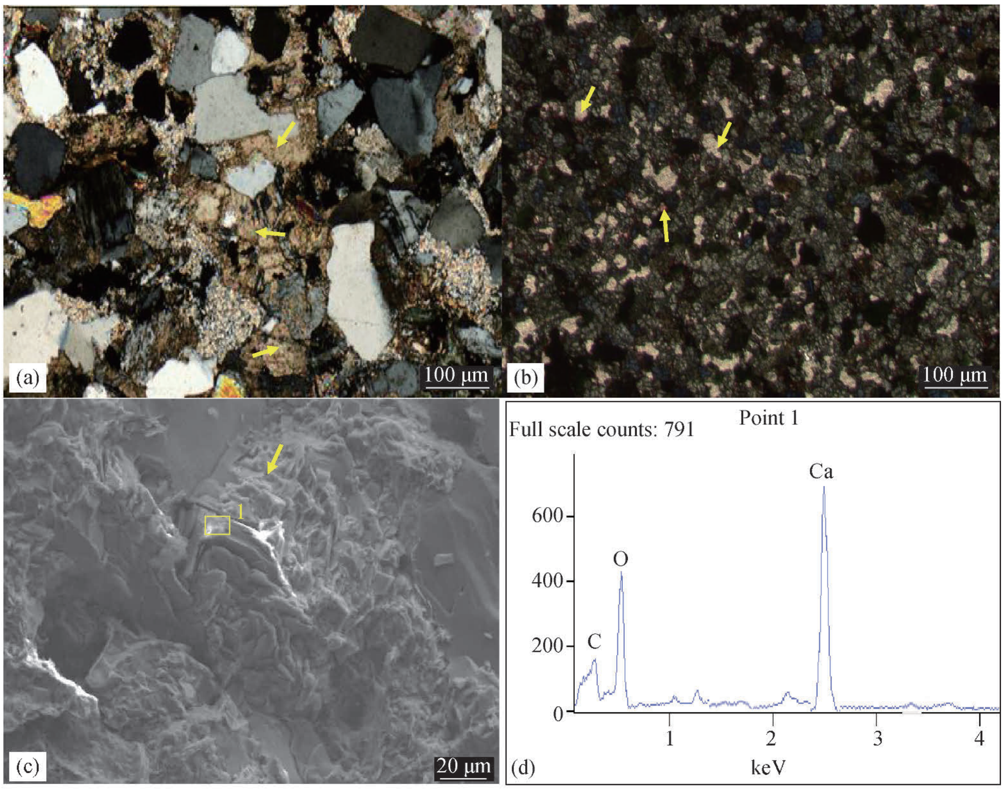

Fig. 5. (a) Photomicrograph showing calcite cement (yellow arrows); (b) ferroan calcite (yellow arrows) filling intergranular pores; (c) SEM (BSE) image of regular rhombohedron calcite (yellow arrow) irregular clevaged calcite; (d) EDX spectrum showing elemental composition of calcite at point 1.

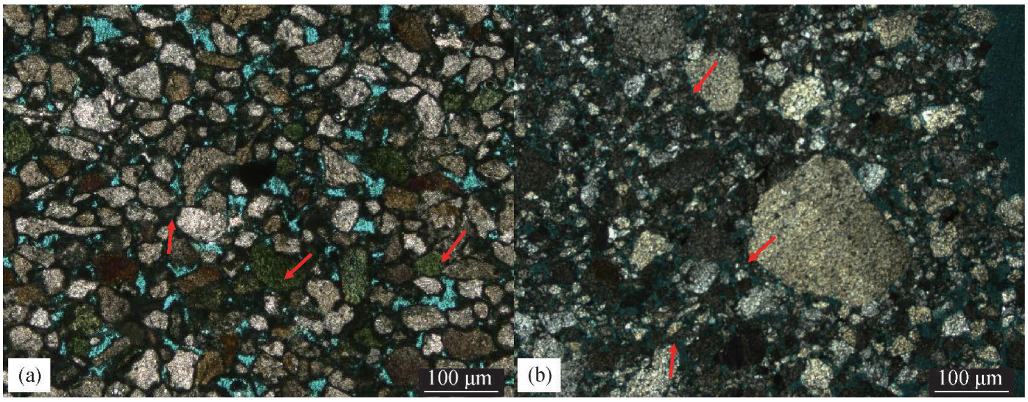

Fig. 6. Thin section photomicrograph of sandstone from borehole E-AJ1.
(a) Precipitation of glauconite in intergranular pore spaces (red arrows); (b) authigenic glauconite as rim or line on the grain surfaces (red arrows).

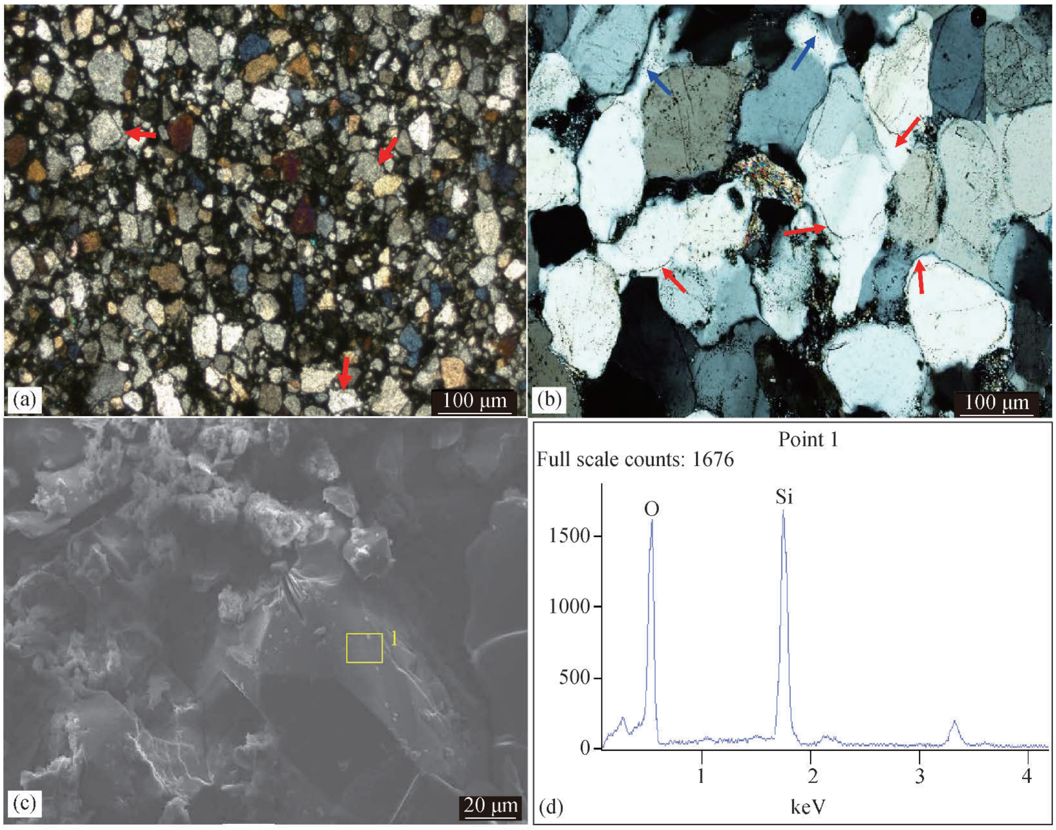

Fig. 7. (a) Thin section photomicrograph of sandstone from Borehole E-AJ1 showing quartz overgrowths (red arrows); (b) thin section photomicrograph of sandstone from Borehole E-D3 showing authigenic quartz cement (blue arrows) and quartz overgrowths (red arrows); (c) SEM (BSE) image of euhedral quartz crystal (left side) with pyramid-like surfaces in sandstone from Borehole E-D3; (d) EDX spectrum showing elemental composition of quartz at point 1.

under plane-polarized light whereas under cross-polarized light, they exhibit high interference colour ranging from third-order green to dark green colour. The occurrence of glauconite cement in sandstones perhaps point to iron-rich, oxidized shallow marine depositional environments.

4.3.1.3 Silica cementation

Silica cement occurs in the sandstones as authigenic quartz in pore spaces and as euhedral syntaxial form around quartz grains as overgrowths (Fig. 7). The overgrowth parts have the same optical properties as the original detrital quartz grains and often gives the grain more euhedral crystal faces. This type of cement is mostly formed due to the precipitation of silica (quartz) into the pore spaces. However, some quartz cements were formed due to recrystallization of the fine matrix minerals. The pore waters required for the precipitation of quartz overgrowths would have been acidic or slightly alkaline, in an environment containing sufficient dissolved silica to allow quartz overgrowths formation. The observed clay minerals tend to prevent the growth of authigenic quartz in the sandstones. Occassionally, there is an iron oxide staining and/or dust lines in the boundaries between the detrital quartz and overgrowths, perhaps sugesting a later development of quartz cement after a period of subaerial exposure. The potential source of silica for the formation of silica cements mainly due to the dissolution of feldspar and mica grains, resulting in additional free silica in the pore fluid. Furthermore, the alteration of one clay mineral to another (i.e. smectite illitization) could release a significant amount of silica into solution as well as the the presence biogenic siliceous material. The dissolved silica of the Bredasdorp sandstones was mostly probably derived from the extensive dissolution of feldspar.

4.3.1.4 Clay cementation

Clay minerals or matrix are the most common cementing materials in the Bredasdorp sandstones, occurring as pore lining and pore-filling cement (Fig. 8). The observed authigenic clay minerals in the Bredasdorp

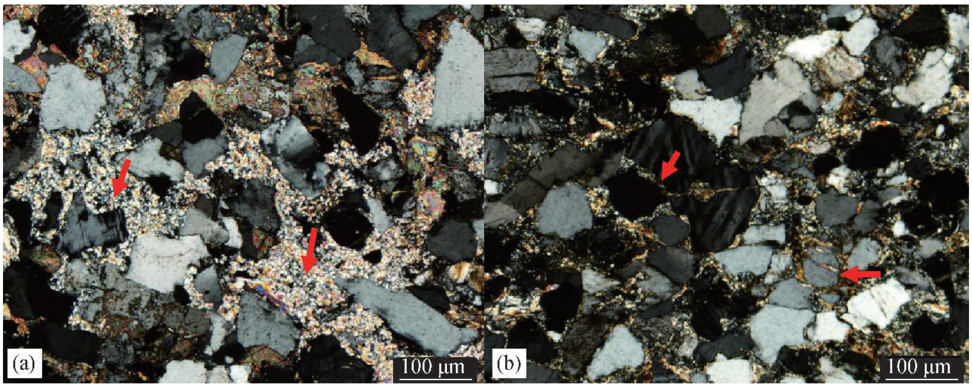

Fig. 8. Thin section photomicrographs of sandstone from Borehole E-AJ1.
(a) Pore filling clays (red arrow); (b) pore lining clays (red arrow).

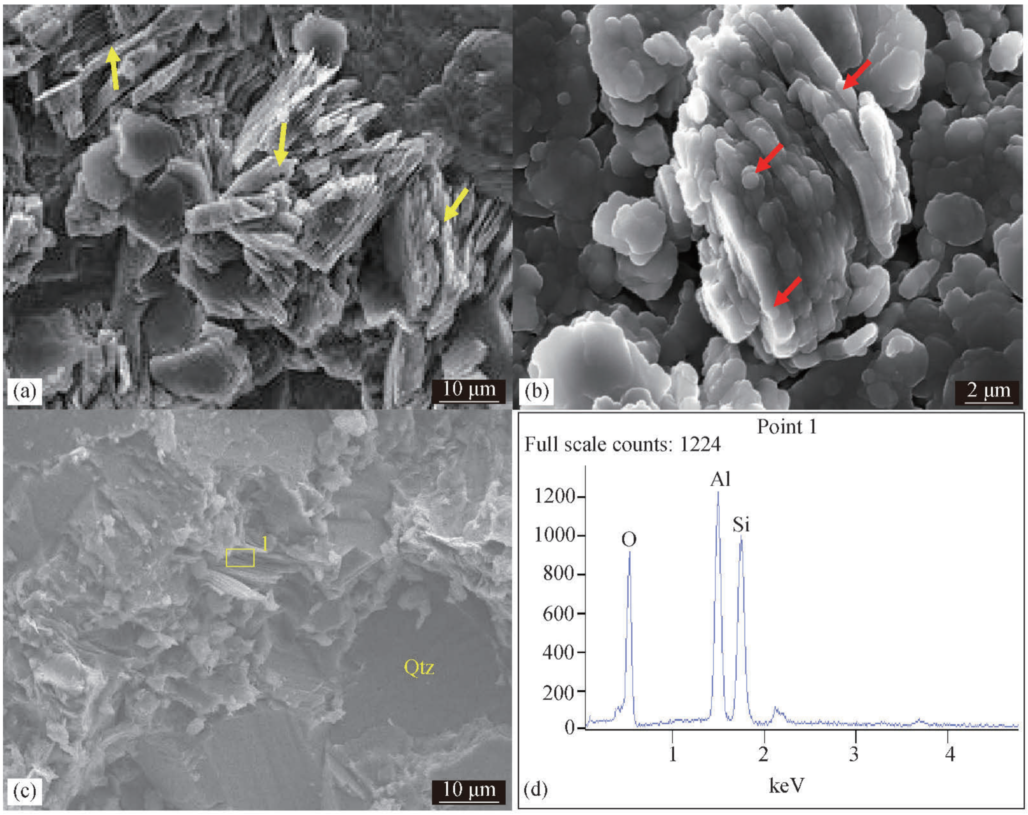

Fig. 9. (a) SEM (BSE) photomicrograph showing aggregates of booklet-like kaolinite (yellow arrows) in sandstone from Borehole E-AH1; (b) SEM (BSE) image showing rod-shaped illite growth (red arrows) from the kaolinite; (c) SEM (BSE) image showing accordion or booklet-shaped kaolinite (yellow box), and quartz grain; (d) EDX spectrum showing elemental compositions of kaolinite at point 1.

sandstones are kaolinite, illite and smectite. These clay minerals are formed as a result of recrystallization of fine matrix and dissolution of K-feldspars. Alternatively, the clay minerals could have been formed due to the alteration of one kind of clay mineral to another (i.e. transformation of smectite and kaolinite into illite).

4.3.1.4.1 Kaolinite

Kaolinite in the Bredasdorp sandstone is observed under SEM as fibrous or booklets and vermicular aggregates in mud matrix and mud intraclast, occurring as pore filling and pore lining cement (Fig. 9). This kaolinite is also observed occurring as replacement mineral, replacing some of the detrital K-feldspar and muscovite grains. Authigenic Kaolinite is the most abundant clay mineral in the sandstones. The formation of kaolinite is dependant on: (1) the availability of adequate porosity and permeability to permit the movement of interstitial pore waters as well as to provide growth space, (2) Presence of K-feldspar and/or muscovite as a source of Al and Si, as well as the availability of pore waters of an acidic pH. The presence of altered K-feldspar and muscovite in the sandstones shows that these minerals serve as sources of silica and aluminum and led to the formation of kaolinite. SEM observation shows that accordion-shaped clay flakes are present as euhedral crystals in the intergranular pores. The kaolinitized intraclasts are seen as relatively large, irregular, scattered patches of kaolinite. Occassionally, kaolinite patches, which are pressed and deformed between the framework grains, fill adjoining intergranular pores, perhaps indicating kaolinitized pseudomatrix. Partially kaolinitized mica is seen as thin, thread-like leftovers of the muscovite, while totally kaolinitized feldspars are observed as patches of kaolinite with distinct remnant outlines, akin in size to the original detrital feldspar grains. Nonetheless, the partially kaolinitized feldspars have detrital feldspar relics. In few instances, the kaolinite is surrounded by quartz overgrowth, suggesting that the kaolinite pre-dates the quartz overgrowths.

4.3.1.4.2 Illite

Illite is observed under SEM as fabric-like and lath-like crystals or vermicular aggregates within mud intraclast and mud matrix (Fig. 10). Illite occurs as pore filling and pore lining of cement and sometimes they are seen as vermicular stacked platelets within kaolinite and oriented perpendicular to grain surfaces. The vermicular platelets nature of the illite which resemble kaolinite possibly suggest that the illites were formed due to partial or complete recrystallization of smectite and kaolinite. Generally, illite formation (illitization) typically happened after the precipitation of kaolinite and smectite which requires high potassium-pore water to achieve under elevated temperature (90°C–130°C) (Morad et al., 2000). In fact, illite formation requires pores fluid and pore space with high potassium (K), aluminum (Al) and silica (Si) compositions wherein these potassium elements for illitization could be supplied by weathered or dissolved

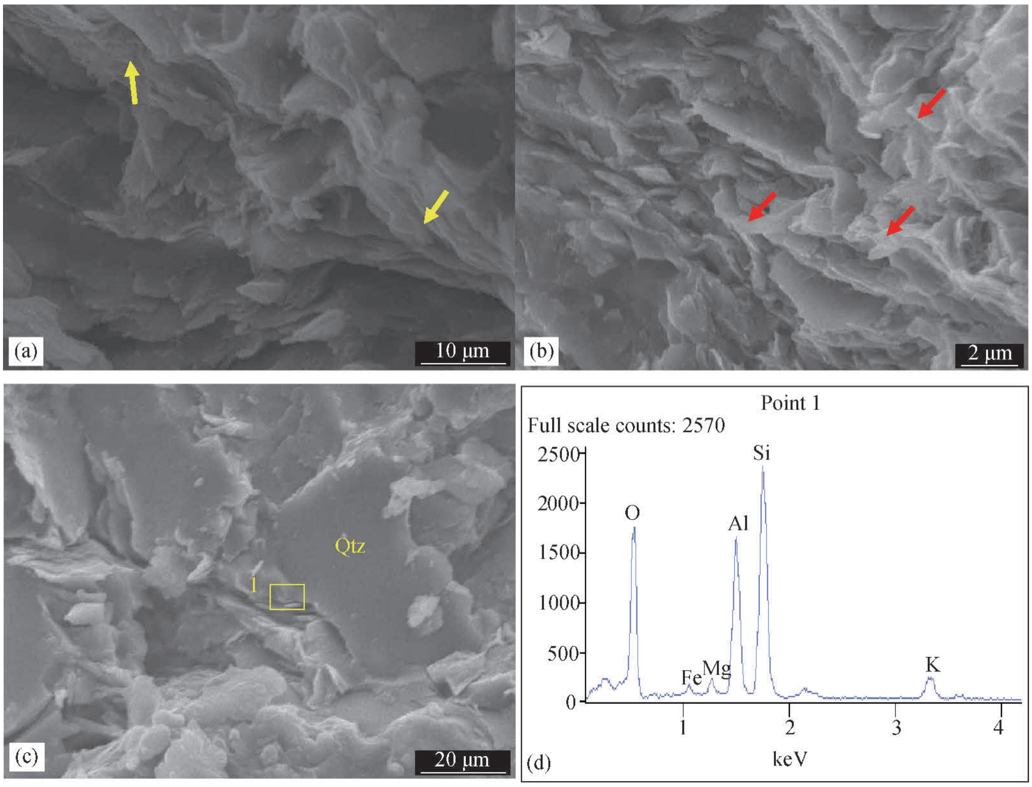

Fig. 10. (a) SEM (BSE) photomicrograph showing fibrous-shape illite (yellow arrows); (b) SEM (BSE) image showing authigenic illite with incipient lath-like or fibrous forms growing from original smectite; (c) SEM (BSE) photomicrograph showing rod/fibrous shape illite (yellow box) and quartz grain; (d) EDX spectrum showing elemental compositions of illite at point 1.

feldspars and kaolinite. Even though illites are frequently associated with the breakdown of kaolinite, kaolinite does not always decompose to form illitic cements and the decomposition of kaolinite does not always led to illitization (Baiyegunhi et al., 2017). Hence, the authigenesis of illite is subject to the alteration of smectite and/or kaolinite as well as other detrital minerals that are easily transformed and required alkaline (illite) and acidic (kaolinite) pore fluid. Illite generally preserves the shape of its predecessors particularly when it is formed as a result of the dissolution of kaolinite. Illite is commonly formed in shallow burial diagenesis in the temperature range of 55°C up to 200°C (Hurst and Irwin, 1982). As temperature increases, smectite is transformed to illite, starting with the growth of single illite pellets on kaolinite for their nucleation (Fig. 10). As mentioned earlier, the development of illite needs a growth medium (pore fluid and space) that has potassium (K), silica (Si) and aluminum (Al) compositions. The EDX graph presented in Figure 10 shows presence of silica, aluminum, potassium, iron and magnesium elements which concur with the chemical composition of illite ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$).

4.3.1.4.3 Smectite

SEM observation revealed that smectite in the Bredasdorp sandstone generally has honey-comb and curved flake (cornflake-shaped texture) shapes (Fig. 11). Occassionally, illites are seen growing from the surfaces of the curved flake smectite, forming a mixed illite-smectite interlayers. The observed smectite occurs as microcrystalline matrix aggregates and grain lining or coating cement. Also, smectite flakes recrystallized to pelletic and fibrous illite through the process of illitization. The chemical composition of smectite shows that smectite is made up of significant amount of elements like Al, Fe, Mg, Si, Ca and Na. During the transformation of smectite to illite or destruction of the mixed illite-smectite interlayers during illitization, substantial amounts of these elements can be released, depending on the original composition of the rock. According to Pallastro (1985), smectite is recrystallized to illite through the process of illitization, wherein potassium (K^+) is added to the mixed interlayer space and the amount of the aluminium tetrahedral (Al^{3+}) have to be increased for the conversion or transformation of smectite to illite (Smectite + Al^{3+} + K^+ = Illite + Si^{4+}) to occur. This is supported or in agreement with the EDX graph presented in Figure 11d. The released silica (Si^{4+}) is thought to have formed or perhaps add to the quartz cement in the sandstones, while the Fe and Mg are alleged to have being formed as part of reaction products that are more stable under the increased burial temperature conditions (Baiyegunhi et al., 2017). As revealed by the EDX spectrum (Fig. 11d), the transformation of smectite to illite also resulted in the increase of the sodium (Na) content in the Bredasdorp sandstones.

4.3.1.5 Sulphide cementation

The pyrite (FeS_2) cement is the least frequent cement type in the sandstones and when present, they are seen in the form framboidal and poikilotopic pyrite cements (Fig. 12). The poikilotopic pyrite cements are very large crystalline pyrites filling secondary pore spaces and are often subhedral in shape. Scanning electron microscopy (SEM) observation has shown that the framboidal pyrites are densely packed with spherical aggregates of submicron -sized pyrite crystals (Fig. 12c). These framboidal pyrites are observed occurring in the pore spaces between grains and coat or surround the grains. The framboidal pyrite is thought to have formed as a result of microbial reduction of detrital ferric iron and typically the presence of seawater sulphate during initial (earliest) burial (Sun et al., 2010). On the other hand, the poikilotopic pyrite which is slightly coarser than the framboidal pyrite can be linked to the decrease in iron oxides (i.e. hematite) present in the sediments, in the presence of hydrocarbons (Elmore et al., 1987). Sometimes, when the pyrite cements are seen in association with carbonate cement, they are observed growing on the carbonate cement crystals, suggesting that the pyrite cements were formed after the carbonate cement. The presence of pyrite in the sandstones signifies reducing conditions, perhaps indicating a deoxygenated environment of deposition.

4.3.1.6 Compaction

The Bredasdorp sandstones show variable degrees of mechanical compaction and little or smaller extent of chemical compaction. Evidence of mechanical compaction in the sandstones include the existence of different types of grain to grain contacts, fracturing of some framework grains as well as the deformation of ductile grains like micas. These sandstones are subjected to moderate mechanical compaction during their progressive burial. The pattern of the grain to grain contact progressively changed from non-contact to point contact, to long contact, then to concavo-convex and sutured contacts (Fig. 13). The average percentages of the point contacts, long contacts, concavo-convex contacts and sutured contacts are approximately 11%, 30%, 41% and 18%, respectively. The overburden that compacts the sands also resulted in minor fracturing of some of the feldspar and muscovite grains (Fig. 13). Progressive burial led to increase in the degree of compaction and resulted in porosity loss either by grain rotation or slippage. This eventually caused the more resistant minerals to fracture or crack, resulting in the dissolution of minerals at grain to grain contacts (pressure dissolution) into an aqueous pore fluid in areas of relatively high stress. Chemical compaction through pressure dissolution was minor in the analysed sandstones and it was only observed in very few samples. Stylolites structures are occassionally seen on the sandstones.

4.3.1.7 Dissolution

Dissolution is a common diagenetic process in the Bredasdorp sandstones and it encompasses the removal in solution of part or all of the previously existing minerals, creating secondary pores in the rocks (Fig. 14). Dissolution usually occur under high temperature in deep burial environment when acidic fluids are in contact with the soluble constituent of the rock and it often serves as a precursor for mineral recrystallization and replacement.

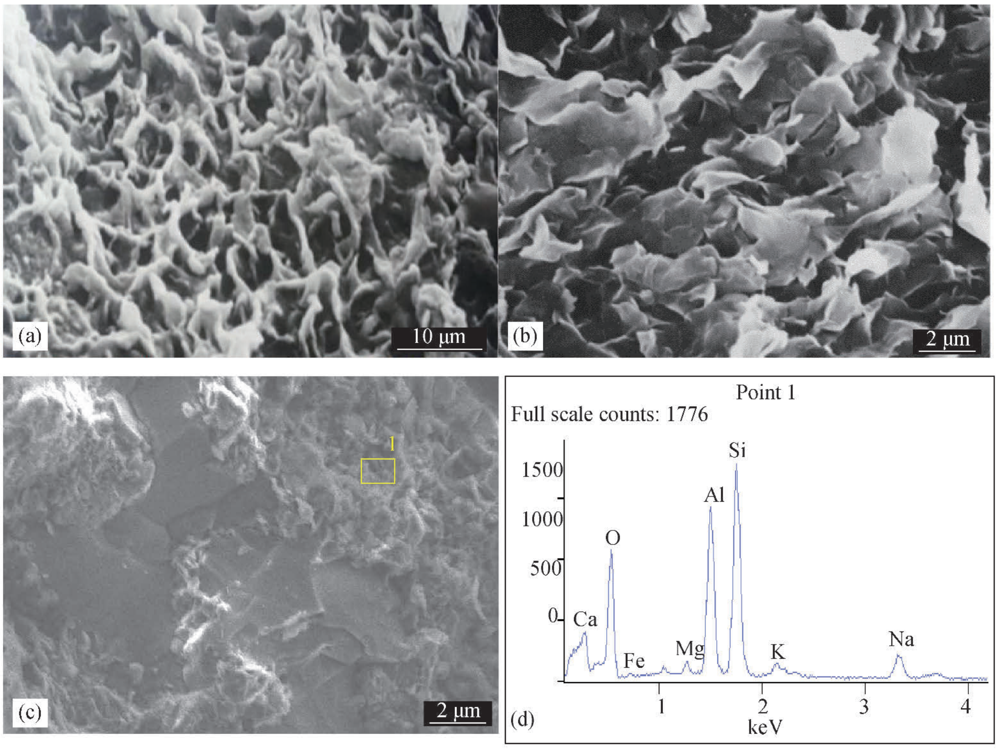

Fig. 11. (a) SEM (BSE) photomicrograph showing showing honey-comb shaped smectite; (b) SEM (BSE) photomicrograph showing mixed smectite-illite layer; (c) SEM (BSE) photomicrograph showing honey-comb shaped smectite (yellow box); (d) EDX spectrum showing elemental compositions of smectite at point 1.

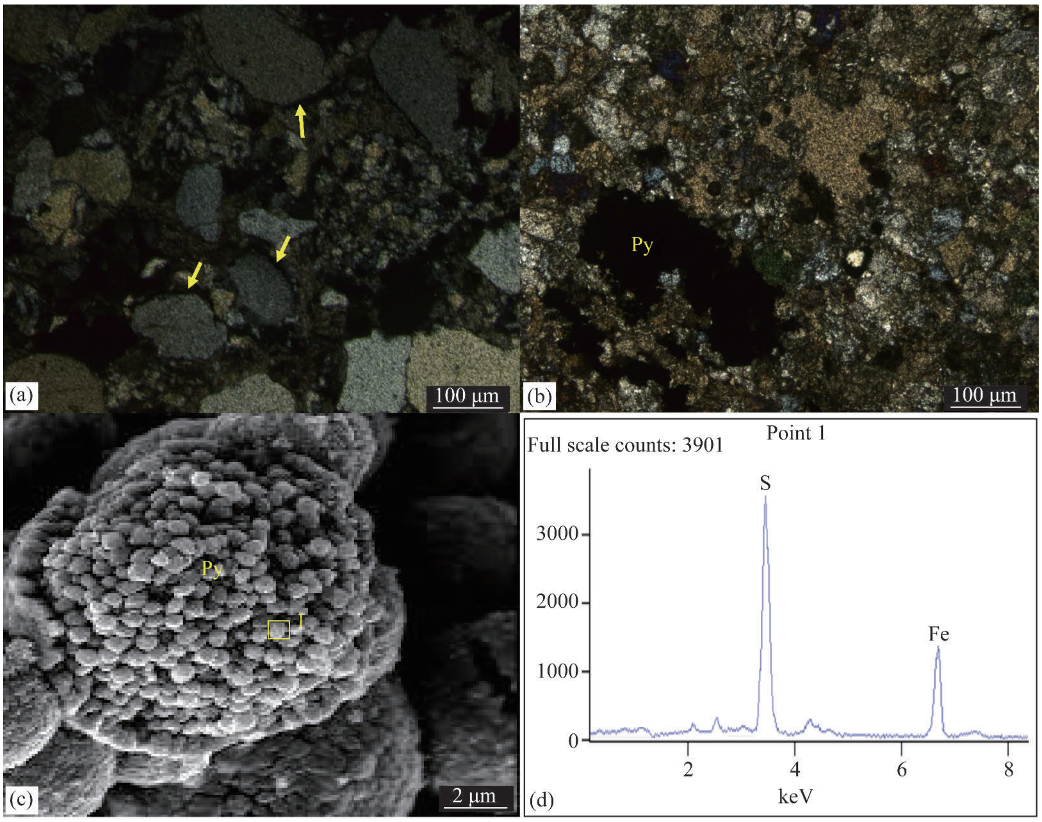

Fig. 12. (a) Photomicrograph showing authigenic pyrite cement in the form of thin rim or patch surrounding framework grains; (b) patch pyrite cement filling the secondary porosity; (c) SEM (BSE) photomicrograph of authigenic framboid pyrite; (d) EDX spectrum showing elemental composition of pyrite at point 1.

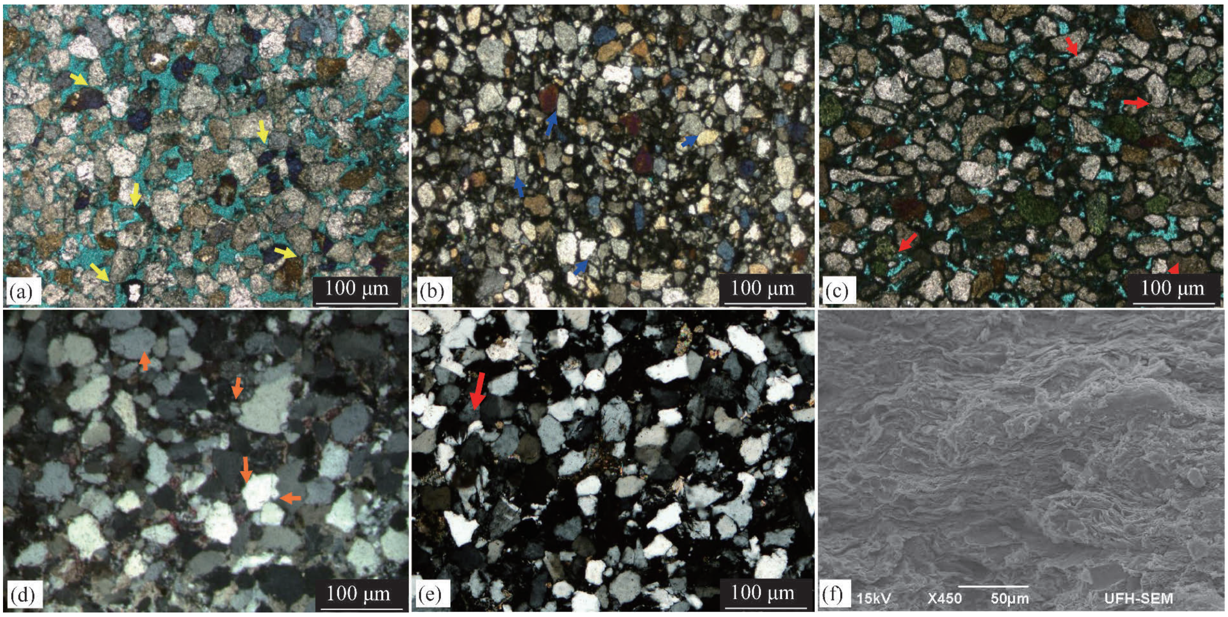

Fig. 13. Thin section photomicrographs of sandstone showing different grain to grain contact patterns due to increasing burial depth.
(a) Point contact (yellow arrows); (b) long contacts (blue arrows); (c) convano-convex contacts (red arrows); (d) sutured contacts (brown arrows); (e) grain deformation; (f) grain alignment and deformation: SEM (BSE) photomicrograph showing orientation and deformation of clays as a result of compaction.

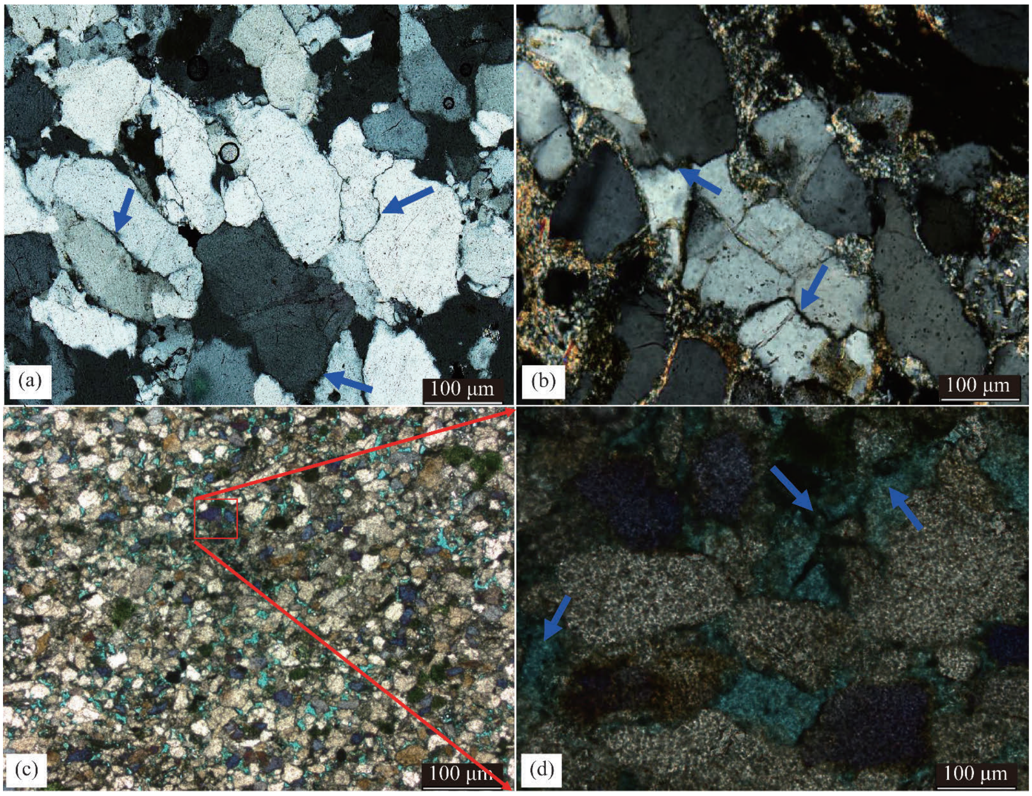

Fig. 14. Thin section photomicrographs of sandstone.
(a–b) Different dissolution cracks (blue arrows) formed by pressure disolution along grain boundaries; (c) secondary porosity as a result of dissolution of feldspar (blue arrows).

The main soluble components in the Bredasdorp sandstones are feldspar and carbonate minerals. SEM observation revealed that some kaolinite and feldspar (albite) grains were formed as a result of the dissolution of weak detrital K-feldspars. Furthermore, the dissolution of these K-feldspars and micas led to the release of silica, consequently providing a silica source for the formation of authigenic quartz.

4.3.1.8 Mineral replacement

Mineral replacement involves the in situ dissolution of one mineral and immediate precipitation of the other. The dissolution could take place over a period of time, with new minerals gradually precipitating and replacing the existing or dissolving minerals. The replacement of one mineral by another mineral is a fairly common diagenetic process in the Bredasdorp sandstones, perhaps as a result of the susceptibility of K-feldspars to modification or alteration in burial diagenesis. As burial depth increases, the prevailing temperature also increases, resulting in some existing minerals to become feeble and unstable. With time, these unstable minerals are displaced and replaced by the more stable minerals in the new diagenetic environment. Mineral replacement may be partial or complete. However, while partial replacement still keep the identity of the original minerals, complete replacement destroys the identity of the original minerals, thus giving a biased view of the original mineralogy of a rock. Petrographic and SEM analyses have revealed that the main mineral replacements in the sandstones of the Bredadorp Basin are the replacement of feldspar with glauconite, replacement of clay matrix and feldspar with calcite, replacement of microcline with albite (albitization), and replacement of one clay minerals with another clay mineral (i.e. kaolinitization and illitization).

4.3.1.8.1 Replacement of feldspar by glauconite

Feldspars are easily liable to alteration whenever there is a change in their diagenetic environmental conditions. The Ca- or K-feldspar framework grains were either totally or partially replaced by glauconite. The initial process of glauconitization of the detrital K-feldspars is seen in the form of small outgrowth (bleb) along the grain boundaries and cleavage planes until the feldspar is totally replaced by glauconite (Fig. 15a). Generally, the glauconite grains and pellets in the glauconitic sandstones are mostly formed as a result of glauconitization/ replacement of feldspars, and clay matrix by glauconite.

4.3.1.8.2 Replacement of clay matrix and feldspar by calcite

Thin section observation revealed that calcite often replaced both the clay matrix and detrital feldspars and glauconite grains, but sometimes replaces some of the quartz grains (Fig. 15b, c). The most affected feldspars were the K-feldspar (microcline) and minor plagioclase. The replacement feldspars by calcite also led to the formation of secondary pores in sands. Partial replacement of glauconite is frequently marked by relicts of glauconite completely surrounded by calcite cements.

4.3.1.8.3 Replacement of microcline by albite

Albitization is the partial or complete replacement of pre-existing alkali feldspar (K-feldspar) or plagioclase feldspar (Ca-feldspar) by albite (Fig. 15d). Albitization reaction needs a substantial input of sodium, which can then enter the crystal lattice by substituting for the potassium in the microcline. Diagenetic albitization of K- and Ca-feldspars is a common diagenetic process in the Bredasdorp sandstones. These albitization often occurred along microfractures, cleavages, and grain contact margins. Occassionally, the observed albitization is associated with the formation of clay mineral (i.e. illite). Hence, the clay mineral appears to be derived from the albitization of plagioclase, or potassium feldspar. K-feldspar mineral grains are predominantly replaced by albite. Nevertheless, in few instances, the precipitation of the albite grain occurs after the partial dissolution of the weak detrital feldspar grain. In this case, K-feldspar is initially replaced by calcite and it was later replaced by albite. Albite formed as a result of incomplete replacement and is often noted or recognised by their blocky to tabular sector extinction patterns under the optical microscope.

4.3.1.8.4 Authigenic clay minerals

Detrital feldspars in the Bredasdorp sandstones are often replaced by clay minerals to various extents. Petrographic and SEM studies revealed kaolinitization and illitization of weak detrital K-feldspar. Occassionally, muscovite grains are partially replaced by clay minerals, particularly along the boundaries (Fig. 15c). SEM observation shows that dissolved K-feldspars are partially to completely replaced by diagenetic clay minerals, especially kaolinite. In places where the replacement is partial or minor, the original feldspar grain outline is still seen or preserved. In such feldspars, kaolinite commonly appear as arrays consisitng of several, parallely arranged and densely packed crystals that attack or penetrate the edges as well as the surface of the feldspar grain. Consequently, relics of feldspars are usually present within the matrix of the kaolinite crystals. Alternatively, in places were the replacement is major or extensive, the kaolinite occur as numerous stacked-like crystals and separate booklets that achieve relatively high intercrystalline porosity and severely penetrate the surface of the feldspar grain.

4.3.1.9 Recrystallization

Mineral recrystallization is observed in the Bredasdorp sandstones and it involves the change in size or shape of crystals of a given mineral, without any signifcant change in their chemical composition. As a result of the changes in temperature, pressure, and composition of the fluid phase, some minerals are dissolved and re-arranged their crystal lattice, forming a series of interlocking crystals that are often larger than the original grains. These existing minerals can preserve their chemical composition and only change in size. In contrast, some existing minerals may be totally changed or transformed into a new mineral with a different chemical composition. Petrographic and SEM studies show that authigenic quartz, feldspars, illite and muscovite are the recrystallized silicate minerals in the sandstones. Pertaining to clay minerals, kaolinite and smectite are transformed into illite through process of illitization. Increase in temperature would caused the illite to be changed to muscovite (muscovitisation) and the muscovite was further changed to kaolinite, generally along the grain boundary as shown in Fig. 16. Some of the quartz cements were observed to have formed as a result of recrystallization of the fine matrix minerals.

4.4 Diagenetic stages

The diagenetic stage in the Bredasdorp sandstones can be grouped into early diagenesis, middle or burial diagenesis and late diagenesis. Time is relative, with the initial or earliest diagenetic changes occurring just after deposition while the most recent diagenetic events are still happening upto this present time.

4.4.1 Early diagenetic stage

The early diagenetic stage encompasses all the processes or changes that the Bredasdorp sandstone underwent from sand until it became a sandstone. These processes usually occurred at or near the sediments surface where chemistry of the interstitial water is mainly influenced by the depositional environment (Chapelle, 1993). The key factors that affect the early diagentic stage are chemistry of the pore water, original mineralogy, and the presence of petroleum-related fluids. In the studied

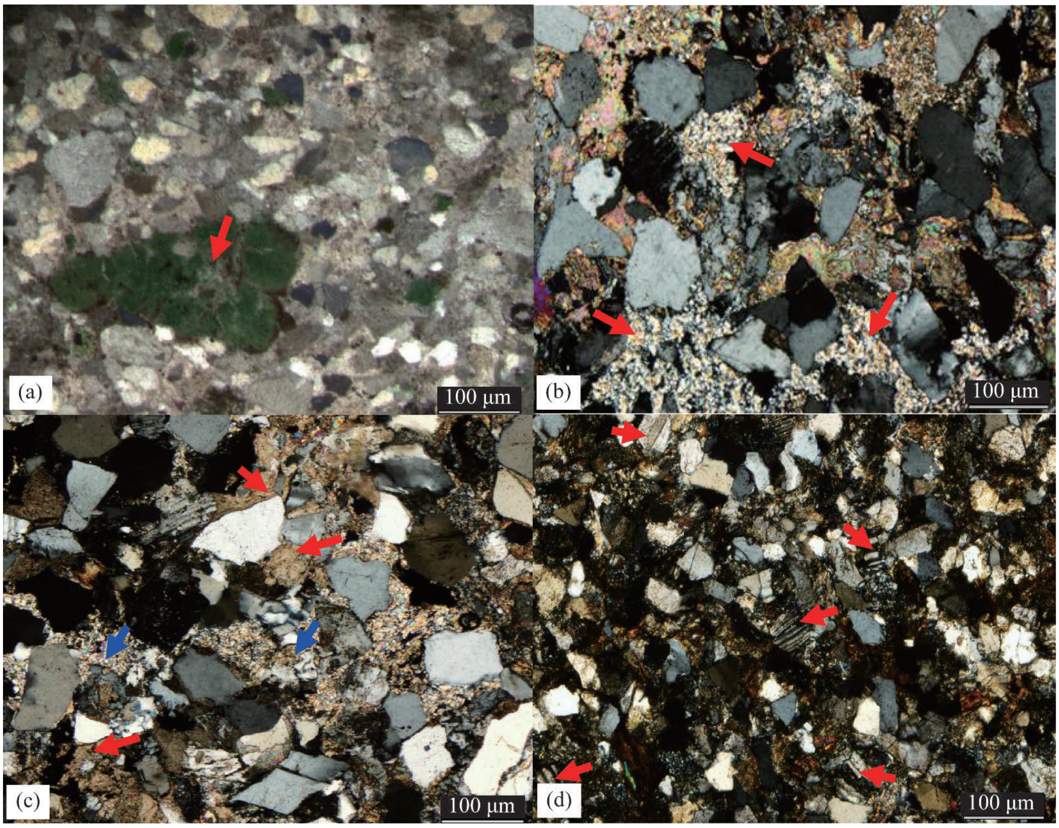

Fig. 15. Thin section photomicrographs of sandstone.
(a) Partial replacement of feldspar and matrix by glauconite (red arrow); (b) partial replacement of feldspar by clay minerals (red arrows); (c) partial replacement of feldspar by calcite (red arrows) and clay minerals (blue arrows); (d) partial replacement of microcline by albite (red arrows).

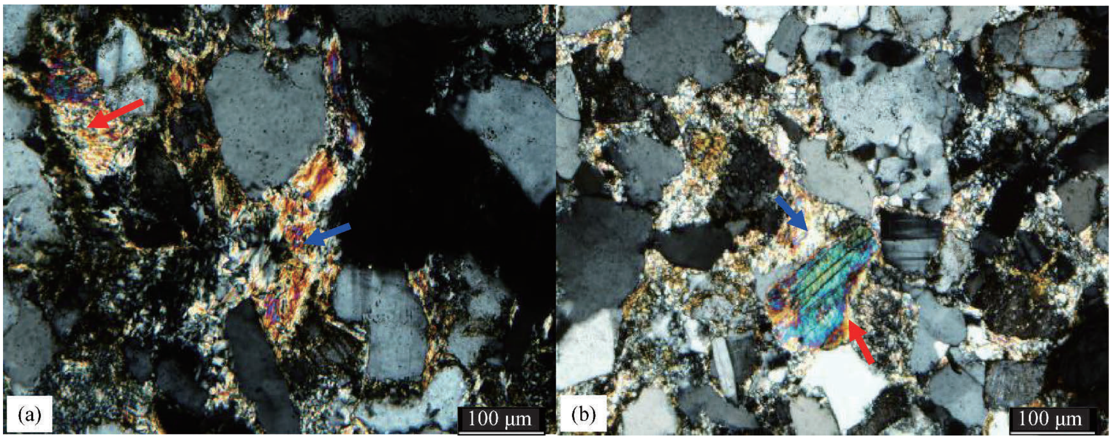

Fig. 16. Thin section photomicrographs of sandstone.
(a) Recrystallization of kaolinite and smectite to illite (red arrow) and muscovite (blue arrow); (b) recrystallization of kaolinite matrix to illite (blue arrow), and also showing illite replaced albite along its boundary (red arrow).

sandstones, the observed early diagenetic processes include precipitation of clay minerals, formation of carbonate (calcite) cement and glauconite as well as early dissolution of grain and minor compaction as a result of increasing overburden. The diagenetic process started with the infiltration of detrital clays and destruction of the primary depositional features (organic reworking). This was followed by the formation of pyrite (i.e. frambroids pyrite) and glauconite, and subsequent precipitation of carbonate cements (calcite). Thereafter, silica cements and authigenic clay minerals precipitated out of the intergranular pore spaces. The occurence of carbonate cement in the loosely packed framework grains suggests that cementation started immediately or shortly after deposition. The authigenic clay minerals in the sandstones are kaolinite, illite and smectite.

The formation of kaolinite requires acidic pore waters (low pH), while illite needs alkaline pore fluids with sufficient K, Si and Al. The ions for the formation or precipitation of kaolinite and illite are mainly sourced from the alteration of detrital feldspars and clay minerals. This acidic pore waters are also produced as CO_2 is released during the diagenetic oxidation of organic matter and it often resulted in the dissolution of the earlier formed carbonate cement. The sands were slightly compacted such that a reasonable portion of the primary intergranular porosity are still preserved. The compaction only involves dewatering and a closer packing of grains which is due to shallow burial depth and absence of overburden pressure. The compaction also resulted in partial leaching of some of the detrital grains. The early occurrence or formation of carbonate cement, especially the poikilitopic calcite cement is noted by the loose grain packing of calcite cemented sandstones. The formation of this poikilitopic calcite cement could be linked to the recrystallization of skeletal materials that existed in the sands as at the time of deposition. The existence of carbonate cementation in the form of calcite cement perhaps suggest an increase in pH and/or temperature of the pore waters. The ions need for the formation of ferroan carbonate cement were possibly derived from alumino-silicate grain dissolution, and clay mineral transformation (Tucker and Wright, 1990). Cementation in the early diagentic stage particularly quartz and calcite cement, prevented significant compaction. The framboidal pyrite cement in the sandstones are thought to have formed below the seafloor. During maximum transgression stages, high rates of flux of dissolved sulphate from overlying seawater would have become reduced to sulphide by bacterial alteration of organic matter, resulting in the formation of the framboidal pyrite (McKay and Longstaffe, 2003). With progressive burial, the fine organic matter preserved in the sandstones becomes involved in diagenetic reactions, contributing reaction products to the pore waters. Quartz cementation also occured as a result of compaction and dissolution, after clay matrix precipitation. The early occurrence of quartz cements in the Bredasdorp sandstones could be due to the decomposition of biogenic siliceous organisms shortly after the deposition of the sands.

4.4.2 Burial diagenetic stage

The middle or burial diagenetic stage covers all the diagenetic processes that happened to the sand during burial, just after the sand had passed from the influence of the depositional environment until lowest temperature and pressure of metamorphism. According to Boggs (2006), the primary factors that influenced burial diagenesis are increased temperature and pressure, change in pore-water compositions and the existence of fine organic material. These factors caused both physical and mineralogical changes while trying to get the sands into equilibrium with the diagenetic environment. The observed burial diagenetic processes in the Bredasdorp sandstones are mechanical and minor chemical compaction, mineral dissolution, recrystallization, precipitation and replacement, as well as pressure-solution, grain-deformation and minor fracturing. Burial diagenesis in the Bredasdorp sandstones started with the mechanical compaction of sands due to increasing overburden pressure. Mechanical compaction brought about the close packing of the detrital framework grains and resulted in the partial loss of porosity. In addition, this compaction is evidenced by long, concave–convex, sutured contacts existing between the framework grains. Detrital micas in the sandstones are commonly bent as a result of the mechanical compaction. Similarly, progressive increase in burial depth due to overburden led to increase in temperature and pressure, resulting in the partial dissolution of feldspars and recrystallization of fine matrix. This feldspar dissolution is common in the Bredasdorp sandstones and it is caused by a relatively acidic condition, in which the stability of feldspars is reduced.

Most of the observed secondary intergranular pores were created by the dissolution of detrital feldspar and carbonate cement. The dissolution of feldspars may also contribute or be responsible for the precipitation of kaolinite. The dissolution of feldspar and associated precipitation of kaolinite needs a pore water with low $(K^+, Na^+)/H^+$ ratios as well as a mechanism to remove the excess silica and (K^+, Na^+) from the system. Fluxing by freshwaters at shallow depths is a likely explanation for such kind of alteration of feldspars to kaolinite (Bjorlykke, 1998). The presence and growth of illite on kaolinite indicates its later origin than kaolinite. The observed dissolution seems to postdate mechanical compaction. Thereafter, precipitation of quartz overgrowths, mineral replacement and alteration of clay minerals dominates the burial diagenetic stage. Albite and illite are formed through replacement of feldspars, particularly the K-feldspars. Most of the K-feldspars are replaced by calcite, with authigenic quartz being released as a by-product. Silicate minerals show an increasing tendency to dissolve with greater burial depths and temperatures whereas carbonate minerals such as calcite are more likely to precipitate (Boggs, 2006). Unstable detrital grains usually release cations to pore-waters, allowing calcite cements to precipitate in pore-spaces or replace detrital grains and matrix. Petrographic and SEM observations revealed that mineral replacements in the sandstones were not only limited to the K-feldspars. Clay mineral alteration in this diagenetic stage includes kaolinite and smectite are being recrystallized to illite, illite was further recrystallized to muscovite, and muscovite is recrystallized back to kaolinite.

4.4.3 Late (uplift) diagenetic stage

The tectonic rifting and associated uplifting of the Bredasdorp Basin (Brown et al., 1995; Jungslager, 1996; PASA, 2012) in the Late Cretaceous period exposed the sandstones to influx of surface water, taking the sandstones into an uplift-related diagenetic environment. This uplift resulted in the decrease in pressure and temperature and caused micro-fracturing as well as the development of granulation seams for accommodation (Ketzer et al., 2003). In the uplift-related diagenetic stage, minerals that were originally formed under high temperature and pressure in the burial diagenetic stage become unstable and are replaced or altered to more stable mineral. Despite the fact that the pore waters in the late diagenetic stage are of low ionic strength, they can still result in substantial mineralogical changes, such as the alteration feldspars to clay minerals, especially kaolinite. Also, previously formed cements (i.e. carbonate) are dissolved (decementation), resulting in porosity increase. Some of the observed kaolinites are formed because of weathering and replacement of feldspars. The kaolinization of feldspars was as a result of the presence of fresh surface-water at uplift. Calcite and kaolinite were also partially dissolved and leached, which led to the formation of secondary porosity. Chemical compaction started at this stage and occurred by pressure dissolution along intergranular contacts and fractures, providing silica for quartz cementation. The precipitation of secondary silica was accompanied, and most likely followed by partial or complete dissolution of the carbonate cements. Quartz overgrowth is well-developed in this stage with little carbonate cement. The quartz overgrowth cement developed or occurred after or postdates the kaolinite cement. Over compaction caused grain fracturing of quartz grains and deformation (bending) of detrital muscovite. Grain fracturing is common at this stage and it increases porosity and permeability as well as creates migration pathways which eases fluid flow in sandstones.

4.5 Paragenetic sequence

A paragenetic sequence has generated for the Bredasdorp sandstones based on the overall relationships of the identified diagenetic processes (Fig. 17). This paragenetic sequence is inferred based on SEM + EDX, XRD and petrographic studies and it shows all the diagenetic events with respect to their relative time of formation. The paragenetic sequence shows that the Bredasdorp sandstones have undergone intense and complex episodes of diagenesis during early, middle and late diagenetic stage.

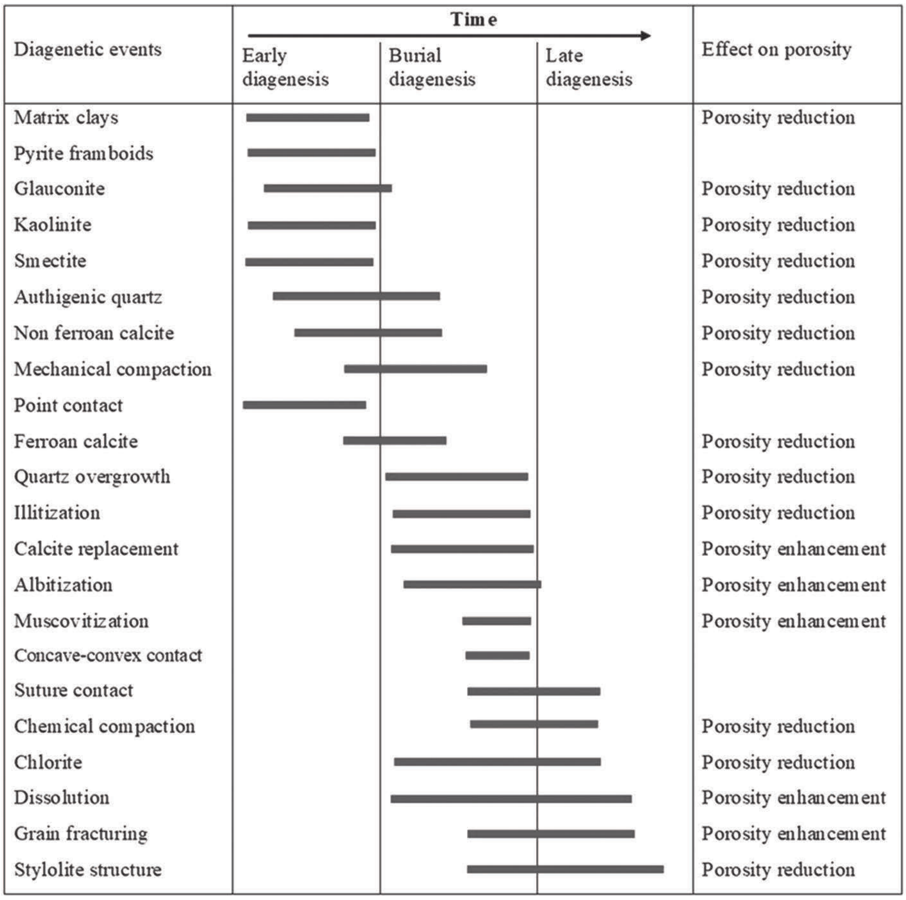

Fig. 17. Paragenetic sequence of the Bredasdorp sandstones as established in this study.

4.6 Reservoir quality

Diagenesis alters the original petrological composition, pore type and geometry of sandstones and therefore affects its resevior properties. Petrographic and SEM studies of the Bredasdorp sandstones shows that the reservoir properties of the sandstones is mainly influenced by diagenetic processes that either reduce or increase their porosity and permeability. The most important diagenetic processes that affected the reservoir quality of the sandstones are mechanical compaction, cementation by carbonate (calcite), glauconite, silica (quartz), sulphide (pyrite) and authigenic clay (kaolinite, illite and smectite) and dissolution of minerals (i.e. feldspar). The inferred potential reservoir quality of the Bredasdorp sandstones is presented in Fig. 18.

Generally, the arkosic sandstones have higher percentages of porosity. These sandstone types could have responded to diagenetical processes differently, thus ensuing in the variation in their reservoir properties. These variations in the porosity and permeability shows the variety of different diagenetic processes that acted to greater or lesser extent on the sandstones in the different boreholes and under different conditions. For example, mechanical compaction causes sandstones with more ductile grains to lose permeability as compared to sandstones with less ductile grains. There is no particular order or pattern of increasing or decreasing of porosities with depth, perhaps suggesting that diagenesis is the main control on reservoir properties. The various controls (i.e., detrital matrix and cements) on reservoir quality acted differently in each borehole and at different depths and sand units. The precipitation of the early calcite cement was either accompanied or followed up by the development of partial pore-lining and pore-filling clay cements, particularly kaolinite. This clay acts as pore choking cement, which reduces porosity and permeability of the reservoir rocks. In addition, the prevalent occurrences of early non-ferroan calcite cement show that

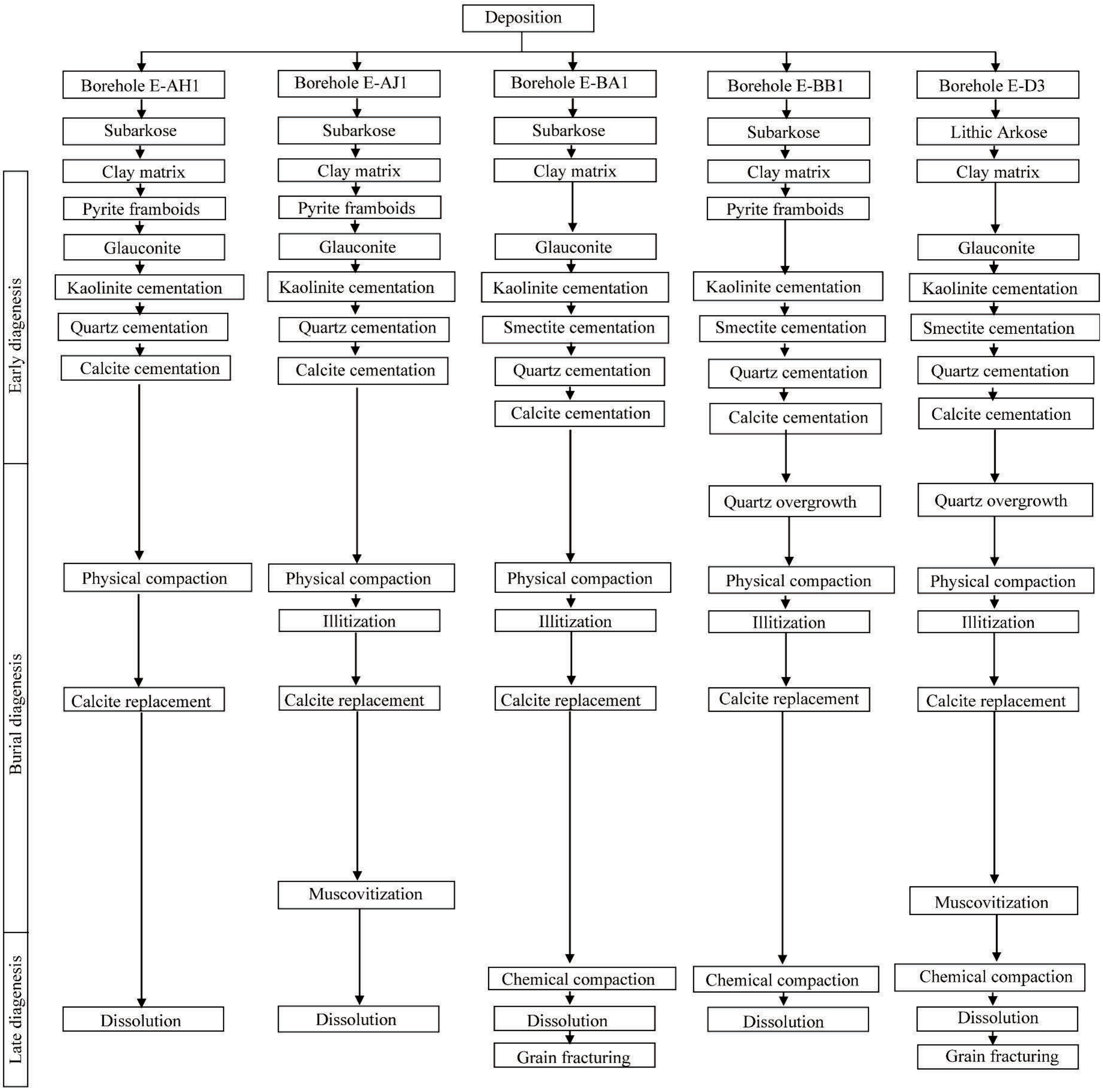

Fig. 18. Flow chart of the main diagenetic processes in sandstones of the Bredasdorp Basin.

the Bredasdorp sandstones lost a substantial amount of primary porosity (i.e. primary intergranular pores and matrix micro pores) at a very early stage of its diagenetic history.

Reservoir quality of the sandstones has been improved to various extents due to the development of secondary porosity as a result of partial to complete dissolution of early calcite cement and some detrital grains (feldspars) and also affected by grain fracturing. In samples where large, isolated secondary pores occurred as a result of grain and/or cement dissolution, often give rise to high porosity and somewhat less permeability. Generally, porosities in the sandstones are significantly reduced by pseudomatrix and silica cements. Permeability has been restricted by the development of fibrous authigenic illite, quartz overgrowths and, to a lesser extent, carbonate and pyrite cements. Most of the samples with poor or low porosity and permeability values have undergone pressure solution along carbonaceous streaks, resulting in more extensive quartz and kaolinite cementation. Also, deeper samples with poor porosities are characterized by pervasive silica cements and development of pseudomatrix, hence, the development of secondary porosity (i.e. solution pores, secondary intragranular pores and fracture pores) is very low or absent. Despite the formation of secondary porosity, diagenesis has significantly reduced the reservoir quality of the Bredasdorp sandstones. The level or degree of impact of diagenesis on the reservoir quality varies differently in each borehole and at different depths and sand units.

5 Conclusions

The Bredasdorp sandstones are largely subarkosic arenite and arkosic litharenite. The primary diagenetic processes that have sturdily affected the Bredasdorp sandstones are cementation and compaction, as well as the dissolution, replacement and recrystallization of minerals. The cements that binds the framework grains of the Bredasdorp sandstones are mainly carbonate (calcite), glauconite, silica (quartz), sulphide (pyrite) and authigenic clay (kaolinite and smectite) cements. Eleven main diagenetic processes are identified in the sandstones and they are categorized into early diagenesis, burial diagenesis and late diagenetic stages. The main diagenetic events in the early diagenetic stage are infiltration of detrital clays, formation of pyrite, glauconitization, carbonate cements, authigenic clays, early dissolution of unstable clastic grains (i.e. feldspar and rock fragments), and minor mechanical compaction. During burial stage, mechanical compaction replacement, recrystallization, replacement and pressure solution and mineral dissolution are the main diagenetic events. The late diagenetic stage is characterized by dissolution (decementation), grain fracturing and development of stylolites. The porosity of the sandstones is influenced by the filling of clay matrix, early authigenic minerals of pyrite and glauconite, and cements such as carbonate (calcite) and silica (quartz). In general, there is no particular diagenetic process that exclusively controls the type or form of porosity evolution in the sandstones. Instead, it seems that the main types of cements (clay minerals, calcite, and silica) and to some extent, compaction collectively controlled the reservoir properties of the sandstones.

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