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Investigation of Facies Types and Associations of Kuhlan Red Bed Formation in NW Yemen: A New Hypothesis for Origin and Depositional Environment

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استقصاء السحنات المصاحبة للطبقات الحمراء في تكوين كحلان – شمال غرب اليمن: نظرة جديدة لأصل الرواسب وبيئات الترسيب

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خلاصة : تم التعرف على 13 سحنة مختلفة في تكوين كحلان والمتمثلة بتتابع من الطبقات الرسوبية السيليسية الحمراء. تمثلت الدراسة بالبحث في العلاقات التتابعية، الصخارية، الخواص الرسوبية وبنيات وبتروجرافية انواع الصخور الشائعة. أمكن من خلال البحث ضم هذه السحنات تحت ثلاث مجاميع رئيسية واضحة. المجموعة السفلى تمثلت بوجود سحنات متبادلة من تتابع رواسب االعكر (رواسب العكر البعيدة) تشمل احجار رملية شملت حجر رملي كتلي، حجر رملي يتميز بوجود تطبق متقاطع وحجر رملي حصوي؛ ومن ثم أحجار غرينية وطفل وقد ترسبت تلك السحنات في بيئات بحرية عميقة وبيئات الرف القاري. أما السحنة الوسطى فتمثل أيضا سحنات من رواسب العكر (رواسب العكر القريبة) حيث أمكن تمييز تتابع من الرواسب البحرية الجليدية المتميزة بالتغيرات الرأسية والجانبية متبادلة مع رسوبيات الحراث والديامكتايت. وقد تميزت هذه السحنات بوجود مايدل على تقدم وتراجع الجليد. وقد شملت هذه المجموعة سحنات رواسب الحراث، ديامكتايت كتلية، ديامكتايت متطبقة، طفلة/حجر غريني مترقق، حجر طيني / حجر غريني مشوه، حجر غريني متدرج الحبيبات، رواهص كتلية، رواهص رملية ذات تطبق متقاطع. كما تمثلت المجموعة العليا من السحنات بوجود تتابع من رواسب الرف القاري البحرية الضحلة تعرض طبقات كتلية سميكة من الحجر الرملي وأحجار رملية تتميز بوجود التطبق المتقاطع يسفلها طبقات من الحجر الغريني والطفل. ويدل التغير في التكوين المعدني وألوان تلك الصخور على تقدم البحر وبداية ترسيب صخور مجموعة عمران الكربوناتية. تعرض بتروجرافية صخور كحلان وجود صخور غير نقية وتتكون من أكثر من 30% مواد طينية كأرضية و 50% من حبيبات الكريستوباليت والكوارتز و 10% مواد لاحمة من الحديد و 10% حبيبات فتاتية من الحديد والفلسبار البوتاسي، وكسرات من الصخور النارية ومواد لاحمة كربوناتية. تم تصنيف هذه الصخور على انها صخور جريوامكي في الأجزاء السفلية والوسطى وصخور أرينيتية مروية مع صخور تحت أركوزية في الأجزاء العلوية

ABSTRACT: Varieties of thirteen facies types were recognized in the Kuhlan Formation represented by red bed siliciclastic sequences of argillaceous sediments. Examination of the Kuhlan stratigraphic column included sequence relationships, lithology, sedimentary characters, structures and petrography of the dominant rock types. These facies types are grouped in three distinct associations of facies. The lower unit A comprises association of facies (Distal turbidites) represented by alternates of turbidity sequences including sandstone, siltstone and thick shale beds. These facies types confirm a regressive depositional environment in deep marine shelf conditions. There are three facies types which are identified as massive sandstone, cross-bedded sandstone and pebbly sandstone facies. The middle unit B association of facies (Proximal turbedites) represents glaciomarine sequences displaying high lateral and vertical facies changes of glacioturbidite sediment alternates with diamictites and tillite beds. The sequences are affected by eustatic and eustatism of the glacial advance and retreat. This unit B includes eight types of facies. These are identified as; tillite, massive diamictites, stratified diamictites, laminated siltstone/shale, deformed siltstone/mudstone, graded rhythmic siltstone, massive conglomerate and cross-stratified sandy conglomerate facies. The upper unit C association of facies is represented by shallow marine shelf sequences displaying very thick massive and locally cross-bedded sand bar sandstone overlying the laminated siltstone/shale interbeds. The upward gradual changes in mineralogical composition and color confirms the start of marine transgression and later deposited platform Amran Group.

Mineralogical composition of Kuhlan sandstone displays impure dirty rocks consisting of more than 30% of argillaceous matrix, 50% of cristobalite and quartz grains, more than 10% of ferruginous cement and 10% of detrital iron oxide grains, potash feldspar, igneous rock fragments and carbonate cement. It is classified as quartz greywacke type in the lower and middle parts and as quartz arenite with subarkoses in the upper part.

KEYWORDS: Kuhlan Formation, siliciclastics, red beds, facies, glacioturbidites, Diamictites, Yemen.

1. Introduction

Lamar and Carpenter (1932) were the first to give the term Kuhlan series to the Kuhlan Formation. Geukens (1966) also used the same term. However, recently this term was changed to Kuhlan Formation by Yemen Stratigraphic Commission (Beydoun *et al*., 1998). A typical section is situated in Kuhlan village, 70km northwest of Sana'a city (Figure 1). The sequence consists of yellowish brown, pinkish and red sandstones (Geukens, 1966). Guekens described a section in the Tawilah escarpment, west of Sana'a, that consists of about 68m sandstones lying above 33m of shaly sediments, which include rounded boulders of Precambrian Basement rocks. The lower shaly part belongs to the newly introduced Akbra Shale (Early Permian) according to Roland (1978) and Kruck and Thiele (1983). The yellow colour of the lower part is gradually changed upwards to reddish yellow. The upper most 6-10m (near Hajjah) is made of sandstone with intercalations of red and gray shale, calcareous sandstone and marl containing shells of mollusks and a carbonaceous layer with plant impressions (Kruck *et al*., 1991). On the basis of fossil evidence this unit was dated as L-M. Jurassic and was deposited in shallow marine to fluvial environment (Diggens *et al*., 1988; Kruck *et al.,* 1991).

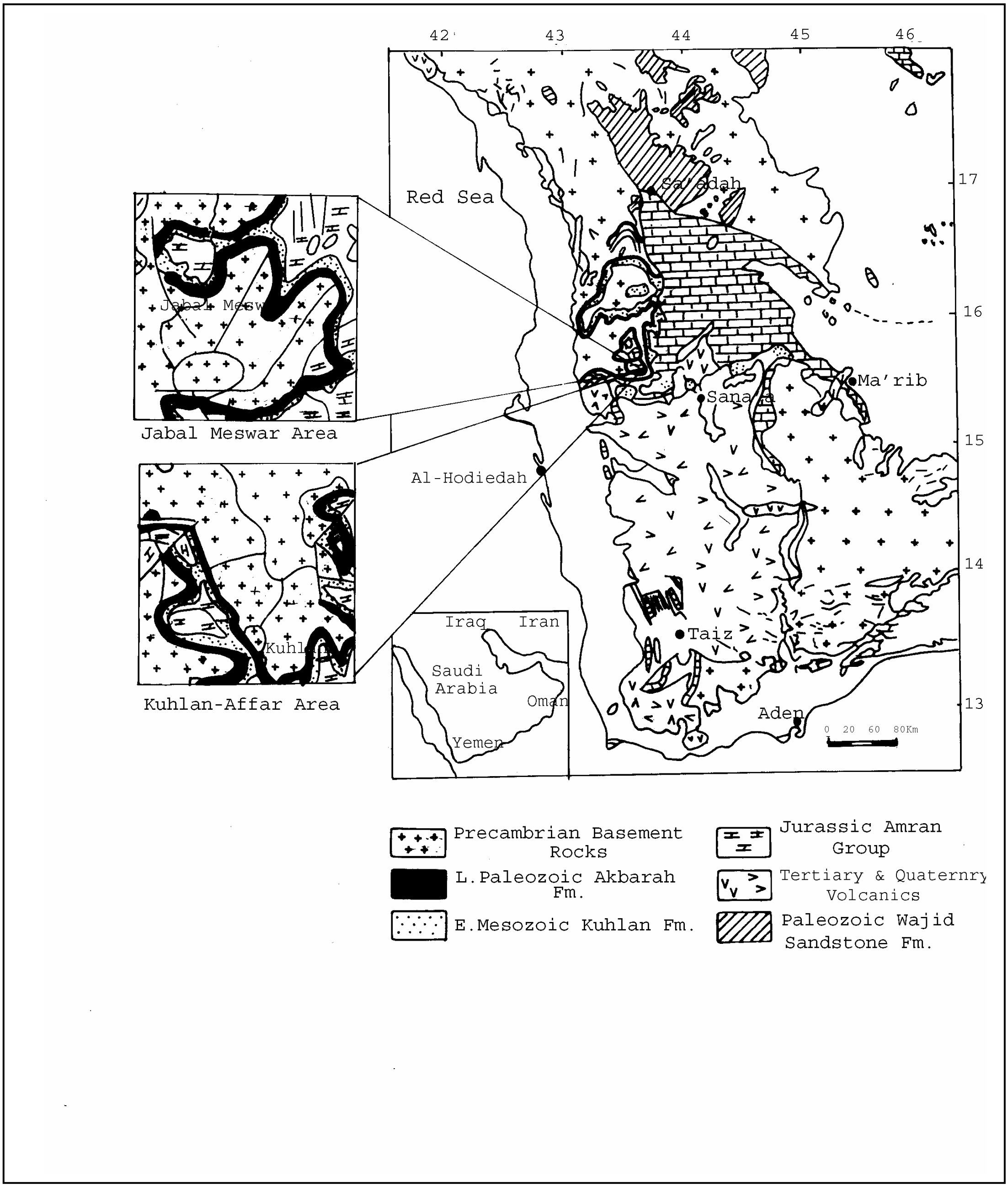

Figure 1. Geologic map of Yemen includes detailed geologic maps of the studied localities (The main trough xis of Kuhlan basin i.e., Kuhlan-Affar and Jabal Meswar) after Kruck *et al.* 1991.

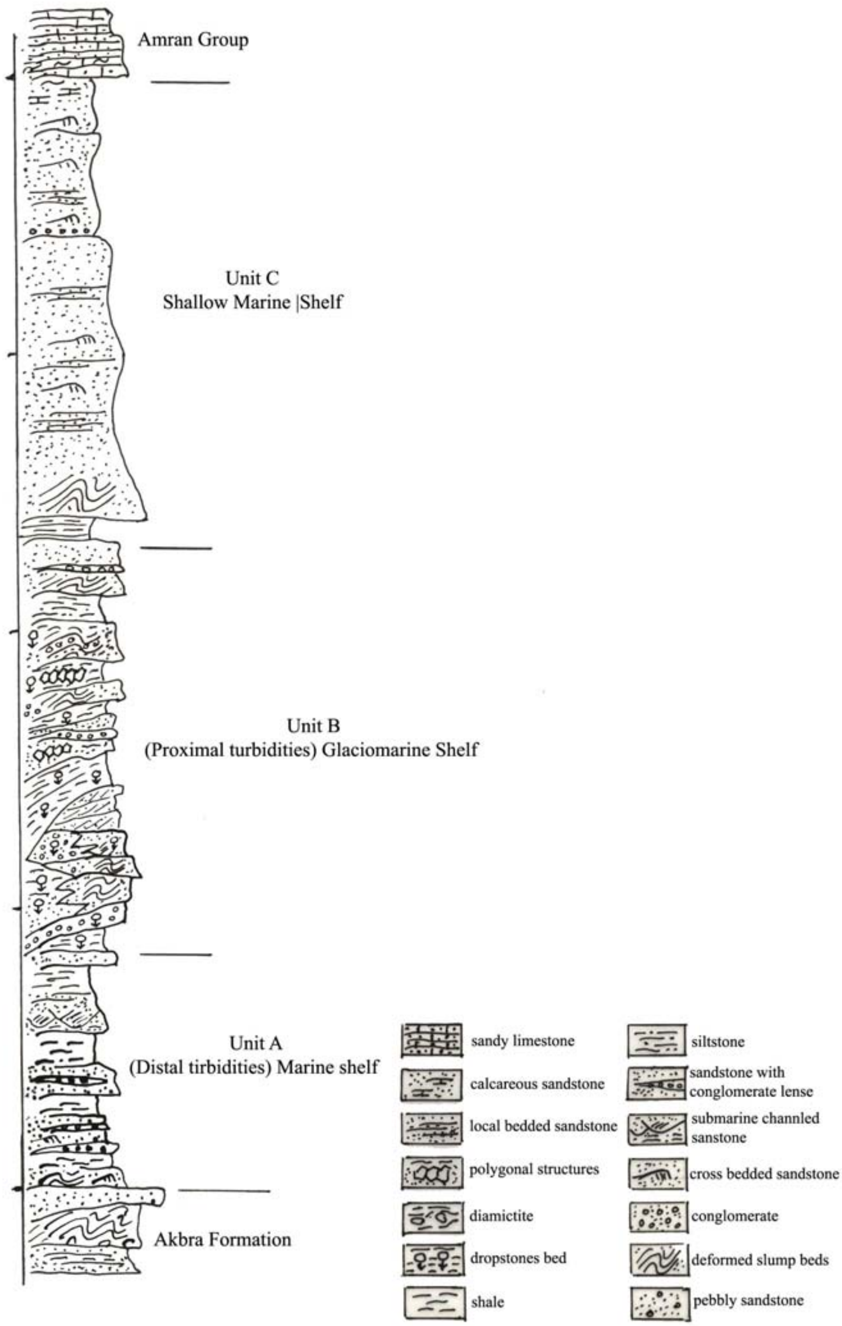

Figure 2. Stratigraphic column of Kuhlan Formation at the type section in Kuhlan village, northwest of Sana'a city.

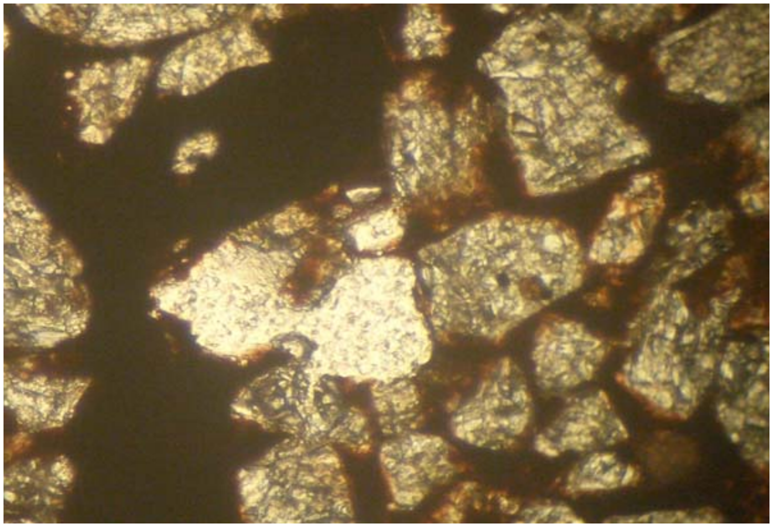

Figure 3. Cristobalite grains floated in ferruginous cement from the greywacke sandstone of the lower part of Kuhlan Fm. Jabal Meswar locality (under polarizer x40X).

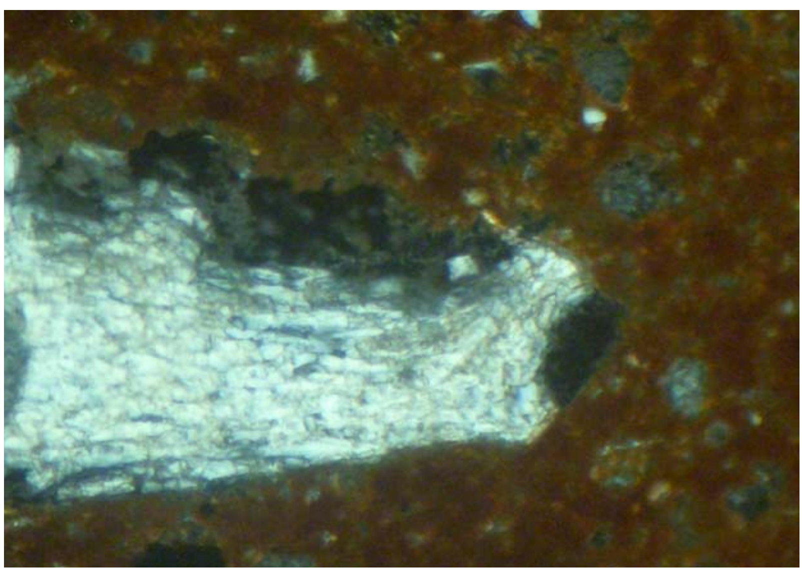

Figure 4. Cristobalite grain floated in ferruginous cement and argillaceous matrix from the eywacke sandstone of the lower part of Kuhlan Fm. In Kuhlan type locality (under crossed Nichols x40X).

1.1 Stratigraphy and gologic setting

Kuhlan Formation (Early-Middle Jurassic) is composed of siliciclastic red bed sequences of yellowish brown to red colour (Al-Subbary *et al*., 2004), massive, bedded and cross-bedded sandstones interbedded with thick siltstone and shale beds of gray and red colour (Beydoun *et al*., 1998). See Figures 1 and 2. The lower unit consists of brown to red, thick bedded, cross-bedded and pebbly sandstone beds interbedded with thick gray to red beds of siltstone and shale (Al-Mashaikie, 2004). The middle unit consists of red beds of conglomerates and sandstones of glaciomarine origin interbedded with deformed stratified diamictite and tillite beds. Huge boulders of Precambrian Basement origin appear embedded within red and gray argillaceous matrix.

Evidence of cyclic turbidity sequences is clearly recognized including varieties of turbidity sedimentary structures, i.e., convolute bedding, contorted slumping beds, ball and pillow structures, etc. Polygonal red sandstone bed is a characteristic structure overlying the glaciomarine sequence in the Kuhlan type locality (Al-Mashaikie, 2004). The upper unit consists of very thick, massive, yellowish brown to red and white sandstones and has a thickness of about 35-40 m, which includes local cross bedding. Sandstones become whitish and calcareous towards the top of the sequence, which is gradually changed into sandy limestone and later to limestone of Amran Group (Al-Mashaikie, 2004). The maximum thickness reaches about 200m in this type of locality and wedges out southwestward and becomes 10m thick at Jabal Bura'a and 14m at Wadi Maksab (Beydoun *et al*., 1998).

Kuhlan Formation gradually overlies the Late Paleozoic Akbra Formation (Al-Mashaikie, 2003) that wedges out southwestward and overlies the Precambrian Basement Rocks, while the upper contact gradually overlies Amran Group.

2. Methodology and analysis

Detailed examinations were carried out on lithology, sedimentary structures, facies and the stratigraphic sequences of the Kuhlan type section. Detailed photography was taken of the different facies types, lithology and sedimentary structures in addition to the whole sequences of Kuhlan Formation. On the other hand, fifty rock samples were collected systematically from the typical outcrops and thin sections were prepared according to the procedure in Tucker (1988). The samples were cut perpendicular to the bedding planes for petrographic study. Microphotographs were taken for different mineralogical constituents in order to define the mineral grains.

2.1 Sandstone composition (Petrography)

Petrographic study of thin sections of Kuhlan sandstone shows that it is composed of more than 30% of cristobalite grains (volcanic variety of quartz, Figures 3 and 4), 20% of quartz in the lower and middle units, 5% of Albite and Potash feldspars (Microcline) (Figure 5), about 5% of igneous rock fragments (both plutonic and volcanic) (Figure 6) and detrital iron oxide grains (Figures 7 and 8) and about 10% of ferruginous cement (Figure 3 and 4). The high content of argillaceous matrix (Figures 5 and 6) may be as high as 30%, making the sandstone of dirty type and classifying it as quartz greywacke type according to the classification sited by Pittijohn (1975). The sandstone of the upper part consists of 30% of quartz grains, 20% of cristobalite grains, 10-15% feldspar grains and 5% of rock fragments. The argillaceous matrix decreases towards the top of the sequence reaching less than 10% with 20% of carbonate and ferruginous cement. This tends to classify the sandstone as quartz arenite with little subarkosic type according to the classification sited by McBride (1963) and Folk (1974). Argillaceous matrix gradually decreases, and is replaced by carbonate cement, towards the top of the sequence. The iron oxide materials in the sandstone rocks appear in two forms, detrital grains and chemically precipitated cement which is highly concentrated in the lower and middle unit.

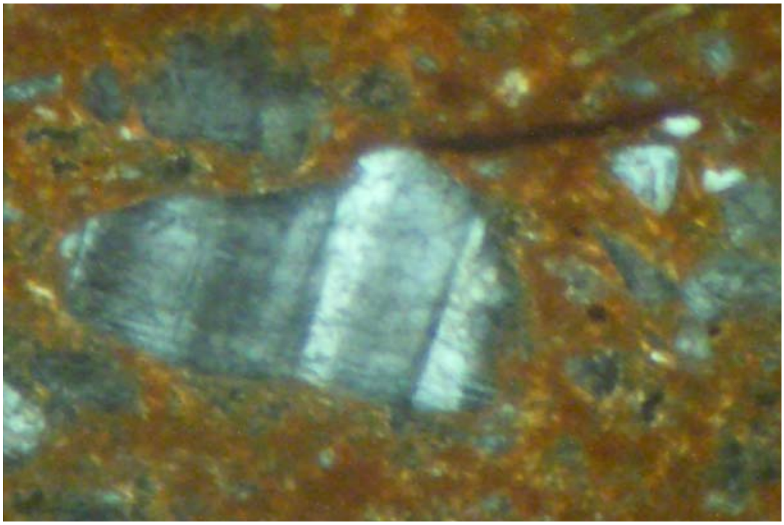

Figure 5. Feldspar (Albeit) grain floated in ferruginous cement and argillaceous matrix from the greywacke sandstone of the middle part of Kuhlan Fm. from Jabal Meswar locality (under crossed Nichols x40X).

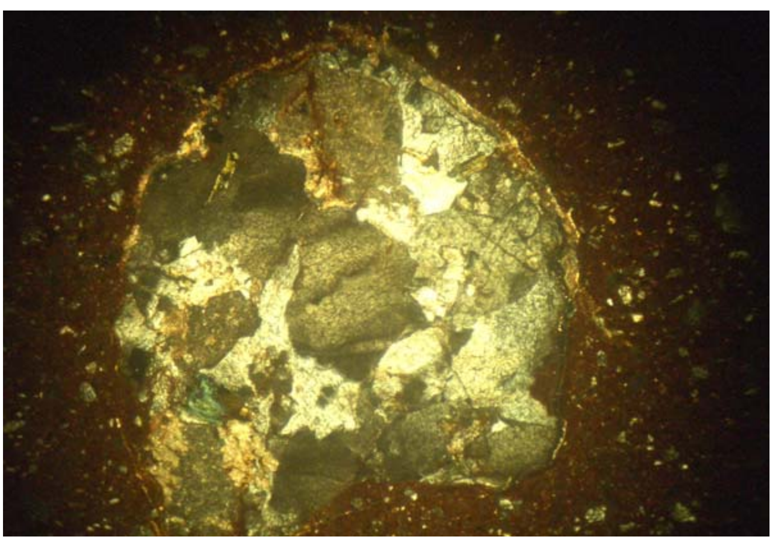

Figure 6. Igneous rock fragment (granite) floated in ferruginous cement and argillaceous matrix from the greywacke sandstone of the middle part of Kuhlan Fm. from Jabal Meswar locality (under crossed Nichols x40X).

Figure 7. Detrital iron oxide grain floated in argillaceous matrix and ferruginous cement from the greywacke sandstone of the lower part of Kuhlan Fm. in Jabal Meswar locality (under polarizer x40X).

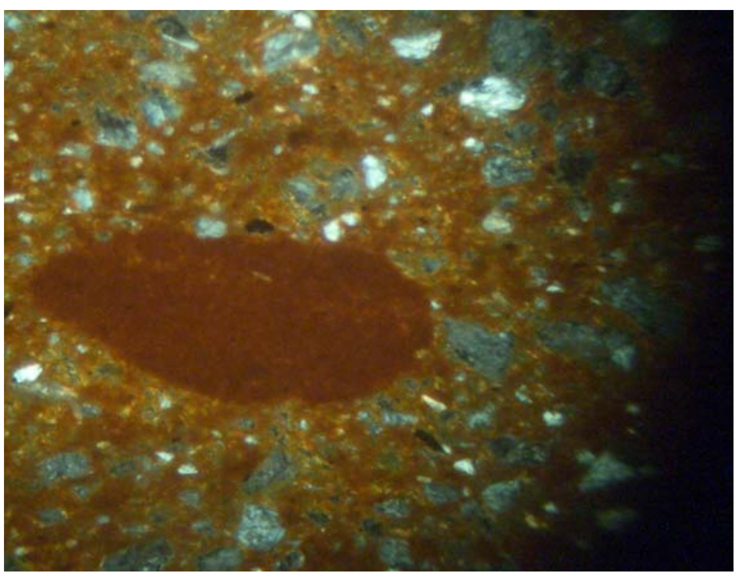

Figure 8. Detrital iron oxide grain floated in argillaceous matrix and ferruginous cement from the greywacke sandstone of the middle part of Kuhlan Fm. in Jabal Meswar locality (under Crossed Nichols x40X).

2.2 Facies types and description

Field observation, examination and identification of different facies types were carried out on lithotypes, sedimentary characters and structures and the relationship between the different sequences.
Kuhlan Formation displays five major litho types distributed throughout the sequences and each of them can be subdivided further into thirteen facies types. These include Sandstone, fine-grained argillaceous facies, diamictite, conglomerates and sand bar sandstone. They are composed mainly of siliciclastic sediments.

2.3 Sandstone (Massive sandstone)

The massive sandstone facies is dominant in all stratigraphic units in the out cropped area of Kuhlan type section. The sandstone is medium to coarse grained has angular to sub-rounded grains and is drab to red in colour. It is composed mainly of cristobalite and quartz grains which are supported mainly with more than 30% of red argillaceous matrix. In the lower and middle units of Kuhlan Formation, the sandstone is classified as quartz greywacke type, according to the classification of Pittijohn (1975), and attains a thickness of 2m, and gets finer upwards (Figure 9). Load structures are well developed horizontally especially in the bedding planes with the claystone beds at the lower most part of unit A. In the middle part, a massive and polygonal red sandstone bed displays a thickness of 1.5-2m (Figure 10). It represents a part of glaciogenic sequences and lies directly above the stratified diamictite. In the upper unit the massive sandstone becomes thicker and whitish in colour reaching a thickness of more than 30 cm and is composed of medium to coarse grained sediments (Figure 11).

2.4 Cross-hedded sandstone

This facies appears in the lower part of the Kuhlan sequences at the locality in Kuhlan village. The sandstone varies in thickness from the common 0.5m to 1m up to 3m and displays normal cross bedding (Figure 12). It is also recognized in submarine channel sandstone (Figure 13). It is composed of fine to medium grained, angular to sub-rounded grains of red in colour. The facies contains high percentages of argillaceous matrix and accordingly is classified as greywacke type (Pittijohn, 1975). This facies is found especially in the lower and middle unit of Kuhlan Formation.

2.4.1 Pebbly sandstone

The pebbly sandstone facies is dominant in the lower part of the Kuhlan sequences. It is of medium to coarse grained including scattered pebbles and cobbles of Basement origin. The pebbles are rounded to subrounded and the facies is drab to red in colour. It is massive, thick and of pale green to red in colour, reaches up to 3m thick, and it gets finer upwards and sometimes becomes part of the turbidity sequence (Figure 14). It includes local cross bedding with signs of paleocurrents directed toward the west and northwest (Figure 15).

2.5 Fine grained argillaceous facies

2.5.1 Fissile shale

The fissile shale facies is dominant in the lower and middle units of the Kuhlan Formation. It is composed mainly of thick fissile shale beds pale green to drab in colour. It ranges in thickness from 0.5m to 3m. It is almost identical to the upper subdivision of the fine upwards sequence of turbidity cycles (Figures 9 and 14). This facies shows deformation and slumping in the middle unit of Kuhlan sequences. This is due to the overriding movements of the glaciers directly above the semi-consolidated sediments in shallow shelf margins (Reading, 1986; Einsele, 1992; Walker and James, 1998; Crowell, 1999).

Figure 9. Thick fissile shale facies (Hammer pointed) lies between the overlying massive sandstone facies and underlying cross-bedded sandstone facies from the lower part (A) of Kuhlan Fm. (Hammer = 0.3m).

Figure 10. Red argillaceous sandstone facies with polygonal structures from the middle part of Kuhlan Fm. (Polygon's diameter= 0.1 - 0.2m).

2.5.2 Deformed siltstone/mudstone

Beds of deformed siltstone/mudstone successions are recognized in the middle unit of Kuhlan Formation. They are stratified, slumped and deformed, showing plenty of micro faults. Some beds show excellent balls and pillow structures composed mainly of sandstone (Figure 16). The facies appears as deformed beds in the figure of convolute contorted stratifications. The facies also includes excellent examples of dropstones. It represents part of the fine upwards Bouma turbidity cycles. Its thickness reaches up to 4m and appears as a reddish green colour.

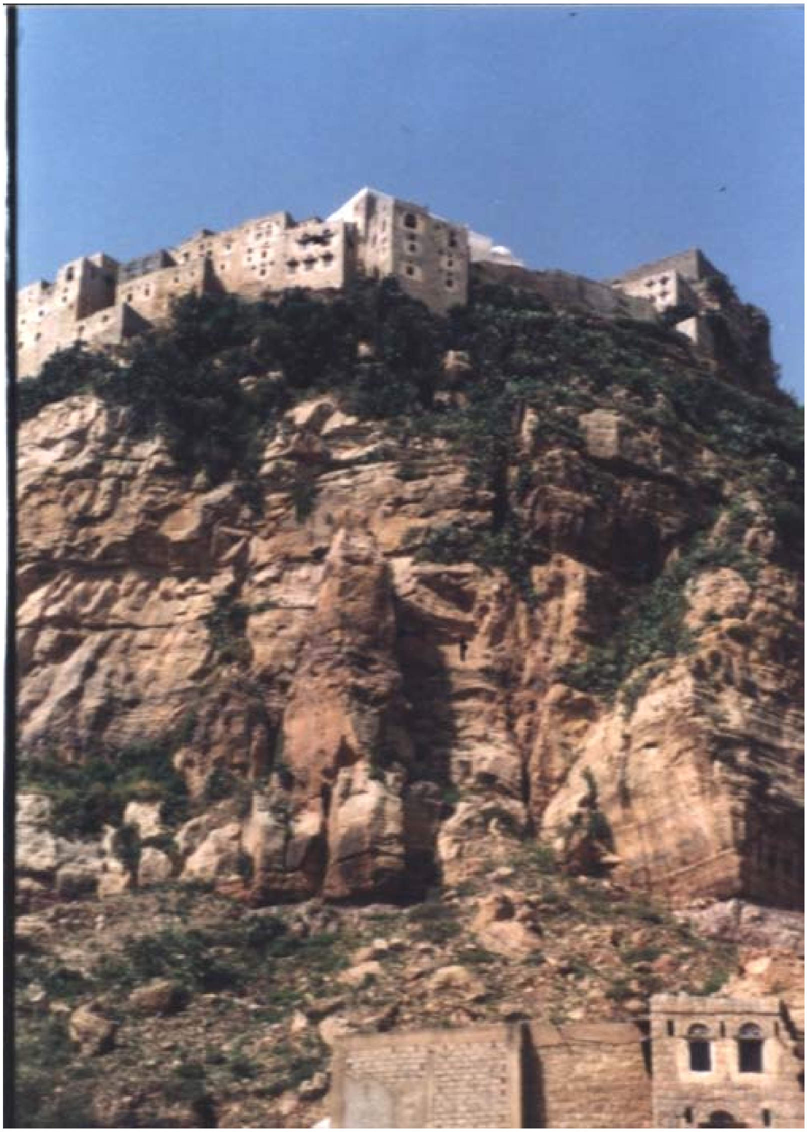

Figure 11. Sand bar, very thick, massive sandstone facies from the upper part of Kuhlan Fm. (Thickness=30-40m). Directly underlain Kuhlan Al-Hesn village and lies above Kuhlan Al-Sooq village.

2.5.3 Laminated siltstone/shale

This facies is clearly recognized in the middle and upper units of Kuhlan Formation. It is composed of dark gray to reddish siltstone/shale interbeds. The whole sequence is laminated and displays a thickness of about 1-1.5m (Figure 16). The facies underlies the very thick and massive sand bar sandstone facies at the start of the upper unit of the formation. Trace fossils of shallow marine varieties appear in the upper contact with the sandstone beds including mainly skolithos and cruziana burrows types. Another variety of trace fossils appears within the stratification of siltstone and shale lamina.

Figure 12. Red bed, cross-bedded sandstone facies from the lower part of Kuhlan Fm. (Pencil=0.1m).

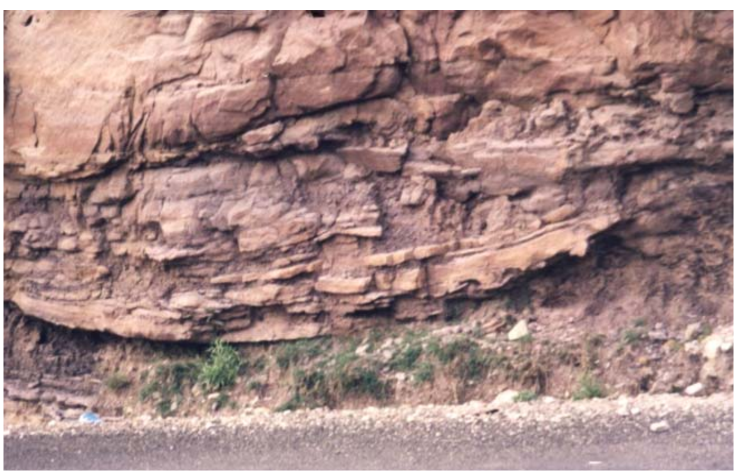

Figure 13. Submarine channel sandstone facies filled with bedded and cross-bedded sandstone and cutting within the fissile shale facies from the lower part of Kuhlan Fm. (Thickness of the channel =1.5m).

Figure 14. Pebbly sandstone facies (Pale green) from the lower most part of Kuhlan Fm. (Roller=0.1m).

Figure 15. Turbidities sequence composed of massive, bedded and cross-bedded red sandstone facies, grades upward to siltstone and shale from the middle part of Kuhlan Fm. (Thickness of massive sandstone in the top =1m).

2.5.4 Rhythmic siltstone

The rhythmic siltstone facies comprises con-scale couplets, which are mainly composed of silt fraction and has been recorded in the middle unit of Kuhlan Formation. The thickness is about 1m (Figure 17). The small scale couplets formed by rhythmic deposition resulted in the glacial environment in which the silt-size sediments are supplied during the winter climatic period (Walker, 1984a; Reading, 1986; Einsele, 1992; Walker and James, 1998; Crowell, 1999; Prothero and Schwab, 1999).

2.6 Diamictite facies

2.6.1 Massive diamictite (lodgment tillite)

The massive diamictite facies was recognized only in the middle unit of Kuhlan Formation. It includes well-rounded boulders and cobbles reaching up to 1-1.5m in diameter, of which the most characteristic is granite embedded within reddish brown argillaceous sandy, silty clayey matrix and lacks any stratification (Figure 18). The thickness of this facies ranges from 1m to 3m. It comprises lodgment or melt-out till (Walker, 1984b; Reading, 1986; Einsele, 1992; Walker and James, 1998; Crowell, 1999) deposited beneath or at the melt snout of retreating glacier within the shelf margins. The origin of the granitic boulders found in the diamictite is probably the Precambrian Basement Rocks, surrounding Kuhlan basin from the northern and southern borders (the Arabian Shield). These sites of Precambrian granite occur in the ancient positive area exposed in the southern margin of the Arabian Shield.

2.6.2 Stratified diamictite

The best exposure of the stratified diamictite lies directly under the Amran-Kuhlan road. It is composed of rhythmic alternates of sandstone, siltstone and shale. Each cycle ranges in thickness from 3 to 5m, including scattered embedded boulders. Isolated boulders similar to those found in the massive diamictite and of different sizes and origins, and mainly derived from the surrounding Basement Rocks, are found scattered within the turbidity sequences (Figure 19).
This facies shows cross-beddings in the sandstone beds with load structures. The sequence appears reddish in colour and shows irregular geometry.

2.6.3 Deformed stratified diamictite

The best exposure of this facies is lies directly under the road of Kuhlan – Affar. It is composed of parallel and cross-stratified sandstone and conglomerate, which is occasionally interbedded with mudstone and diamictite (Figure 20). It is of about 4m thick. The facies assumes irregular shaped beds with sharp, gradational and overturned deformed contacts. The movement of the overriding glaciers deformed the semi-consolidated sediments in shallow shelf margins and displays deformation of the underlying beds (Marmo and Ojakangas, 1984; Walker, 1984a; Reading, 1986; Einsele, 1992; Walker and James, 1998; Crowell, 1999; Prothero and Schwab, 1999).

2.7 Conglomeratic facies

2.7.1 Massive conglomerate (gravel lag)

This facies is found directly under the road near Kuhlan village. It consists mainly of ramps or lags of gravels supported with reddish sandy argillaceous matrix. The thickness of this facies ranges from 3m to 4m (Figure 21). It has an irregular shape and assumes a lense-like shape. It is red in colour, very hard, massive, and strongly supported with argillaceous and ferruginous cement. The lithofacies lacks any of the present structures. Neither sedimentary structures nor any fossil content are observed.

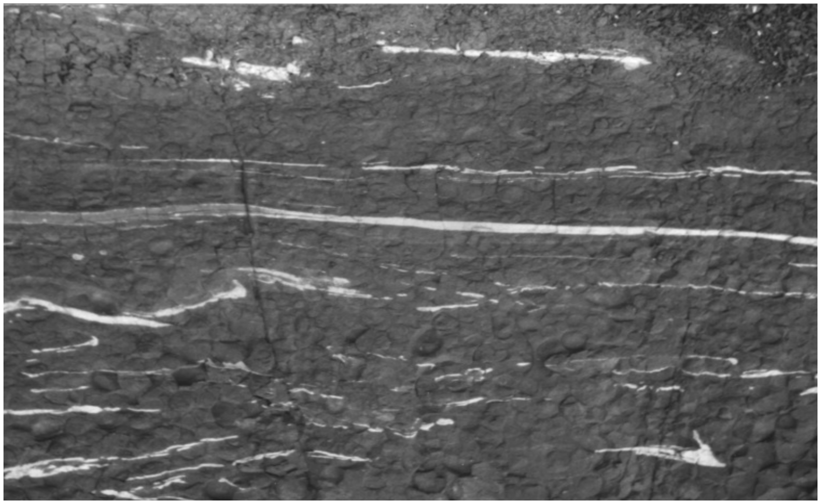

Figure 16. Deformed green siltstone/mudstone facies underlain with laminated siltstone /shale facies from the middle part of Kuhlan Fm. (The sequence= 1m).

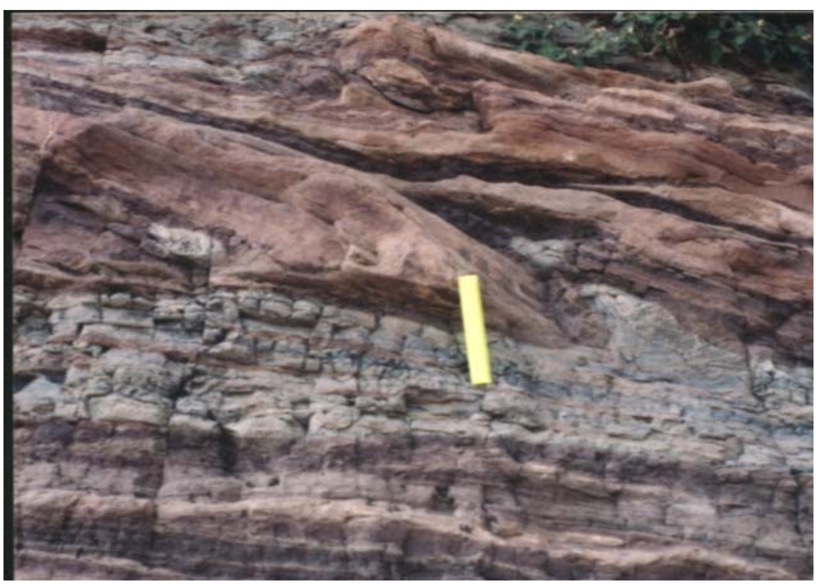

Figure 17. Graded rhythmic siltstone facies from the lower part of Kuhlan Fm. (Roller=0.1m).

2.7.2 Cross-stratified sandy conglomerate

This facies is composed of gravels, pebbles and pebbly sandstone supported with fine argillaceous matrix. It attains a maximum thickness in excess of 4m (Figure 22). The signs of paleocurrents exhibit directions towards the northwest. The suggested origin is of submarine outwash facies, which is deposited under the influence of melt streams outwash (Marmo and Ojakangas, 1984; Reading, 1986; Deynonex *et al.*, 1991; Einsele, 1992; Walker and James, 1998; Crowell, 1999; Prothero and Schwab, 1999).

Figure 18. Massive diamictite facies from the middle part of Kuhlan Fm. (Thickness=1.5m).

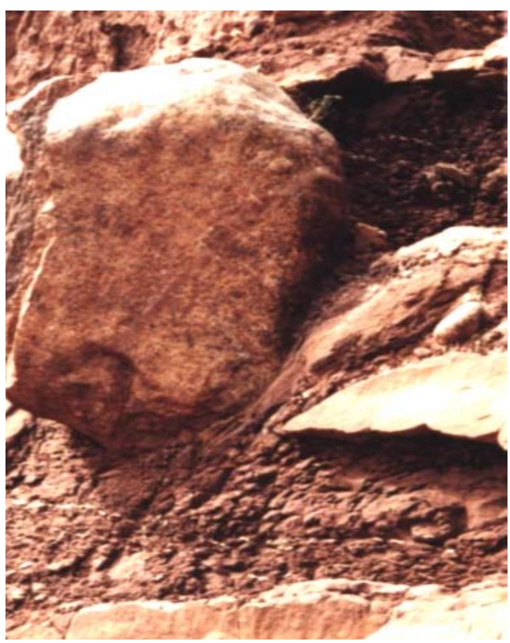

Figure 19. Granitic dropstone embedded within red bed shale of turbidity Bouma sequence (stratified diamictite) shows the fall out.

2.8 Sand bar sandstone facies

The best outcrops of this facies are exposed directly above the Kuhlan village, with further best exposure recognized at the road of Kuhlan-Affar. It represents an important characteristic of the upper part of the Kuhlan stratigraphic column. It is composed of sand bar bodies reaching more than 30m in thickness (Figure 11). It is naturally massive with local cross-bedding, whitish brown to white and has subangular to rounded grains and medium to coarse grains of siliciclastic sediments. It is interpreted as large sand bar bodies, which are deposited in shallow marine shelf margins (Turner, 1980; Walker, 1984b; Reading, 1986; Einsele, 1992; Walker and James, 1998). This facies lies above 1-2m rhythmic and laminated siltstone/shale, where the siliciclastics sequences gradually change upwards to calcareous sandstone in the upper most part and later to limestone of the Amran Group.

3. Classification of facies associations

3.1 (Distal turbidites) deep marine shelf facies association “the lower unit A”

3.1.1 Description

Successions of facies types comprising distal turbidites and attaining a thickness of about 40m, were recognized in the lower unit A of the Kuhlan Formation. The sequences found are alternates of thick, massive and local bedded dark green, fine-grained sandstone beds ranging in thickness from 1 to 2m, with thick, dark green to gray fissile shale beds reaching a thickness of up to 3m. Irregular and lense-like pebbly sandstone beds and sometimes conglomerates of 0.5 – 1m thick are found interbedded with the alternates of sandstone and shale. The sequence displays characteristic sedimentary structures of distal turbidity conditions represented with graded beddings, balls and pillow structures, load, prod and groove casts, contorted slump beddings, etc. Submarine channel and the slump convolute beddings are the most repetitive structures recognized in the lower unit A.

The sequences comprise alternate finer upward Bouma turbidity cycles. These facies associations show gradual increases in grain size upwards up to the middle unit. On the other hand, facies types display a change in colour upwards from dark green and gray to drab and reddish brown to red. The sandstone is of greywacke type classified according to the classification sited by Pettijhon (1973). The sequences of the lower part reach up to 40m thickness which is clearly exposed in the type section and locality at Kuhlan village. The lower part of Kuhlan Formation is lying conformingly over the Akbra Formation of Late Carboniferous – Permian age (Al-Mashaikie, 2003). Complete turbidity cycle displays the following characteristics from base to top:

1. 0.5m up to 1m of pebbly sandstone to conglomerates displays lense-like and irregular shape beds. The sediments appear to fill the submarine channels. The irregularity of the erosional sole depends on the grain-size of the sediments. Coarse to medium sandstones are generally associated with smooth erosional sole. Gravelly to pebbly sandstones fill more irregular surfaces with steep side scours upto 0.5-1m deep. This horizontal structure which passes progressively into the overlying medium-grained sandstones is generally structureless, but shows in some cases crude horizontal bedding.
2. 0.5m to 1m of medium-grained siliciclastic sandstones with more or less well defined parallel flat to slightly undulating stratifications and some times display normal cross beddings.
3. About 0.3m to 0.5m of fine grained rippled siliciclastic sandstones figured fining upward to siltstone and shale having 1-2m thick beds.

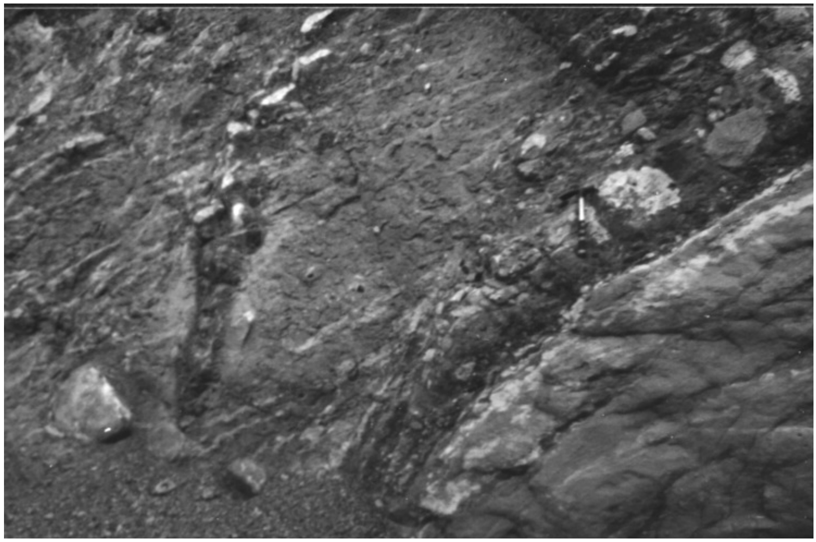

Figure 20. Deformed stratified diamictite facies from the middle part of Kuhlan Fm. (Hammer=0.3m).

Figure 21. Massive conglomerate facies from the middle part of Kuhlan Fm. (Pencil=0.1m).

3.1.2 Interpretation

Subaqueous streams are the proposed origin for the conglomerates locally preserved on the original bounding surface or in submarine channels. The proposed origin of subaqueous streams were probably coming from the annually melting of remnant glaciers of the Permo-Carboniferous period, residual on the positive height in the surrounding areas (Al-Mashaikie, 2003). This interpretation is based on the presence of rough cross stratifications, pebble imbrications, pebble shape and limited lateral extent (Walker, 1984a; Reading, 1986, Deynoux *et al*., 1991; Einsele, 1992; Walker and James, 1998; Crowell, 1999). The annual flows of subaqueous streams create turbidity currents, which are probably associated with the earthquakes coming from the rift movements of Kuhlan basin.

Figure 22. Red cross-stratified sandy conglomerate facies from the middle part of Kuhlan Fm. (Pencil=0.1m).

Alternates of sandstone with siltstone and shale beds confirm deep shelf marine conditions, preserved between the underlying emissive erosional surface and the overlying transgressive surface (Demarset and Kraft, 1987; Nummedal and Swift, 1987; Deynoux *et al*., 1991). The latter surface is lapped by sandstone bars which are interpreted as inner shelf sand ridges accompanying the shore face retreat of the upper part of the formation. The lower part sequences of Kuhlan Formation display analogies with the Bouma turbidity cycles as evidenced by:

1- Repetition of fining upward sequences.
2- Upward succession of pebbly, massive, parallel laminated, rippled sandstones.
3- Good lateral extensions.

However, the occurrences of sediment gravity flows might appear quite surprising at first glance except in the context of glacial environment whose input is evident in the middle part of the Kuhlan Formation.

Mechanisms by which sediment gravity flows are settled have been discussed and applied to deep sea fan models in a great deal of literature (e.g. Bouma, 1964; Carter, 1975; Middleton and Hampton, 1976; Nardin *et al*., 1979; Lowe, 1979, 1982; for references, terminology and classification). Turbidity sequences have also been reported in shallow water environments of both shallow and deep shelf (Hubert, 1972; Thompson, 1972; Scott, 1975; Homewood, 1983). All these resedimentation processes take place when ice-marginal fans, deltas, and other build-ups become unstable from oversteepening due to either rapid sedimentation, glacier motion or iceberg calving, increased overburden pressure or load, storm wave agitation or earthquakes. If the mechanisms which caused the coarse and fine sand size sediments of the sequences to settle down are related to sediment gravity flows, the ensuing high density current process could be envisaged according to the terminology of Lowe (1982). The sequences range from coarse to gravelly fully turbulent flow (horizon 1), to a more dilute and laminar sandy flow (horizon 2) with traction suspension deposition shown by flat laminations and occasional rippled cross laminations. Depressive pressure remained active in the overlying laminated sandstones of horizon 2 where traction carpets are represented by inversely graded micro conglomerate streaks.

Several authors described shallow water graded sand beds with a vertical succession of structures that resemble those of deep water turbidities as related to storm effects (Kelling and Mullin, 1975; Brenchely *et al*., 1979; Hamblin and Walker, 1979; Nelson, 1982; Dott and Bourgeots, 1982, 1983; Walker *et al*., 1983; Walker, 1984b). Two phases overlapping in time are recorded in storm deposits: an initial phase of transport and deposition which emplaces the sand on the shelf, and a second phase during which the sand is reworked by storm waves (Brenchely, 1985). Among others (wind-forced currents and storm-surge ebb currents) turbidity currents have been postulated to be responsible for the initial phase (Hamblin and Walker, 1979; Walker *et al*., 1983; Walker, 1984a). Such currents lead to the formation of Bouma subdivisions which are somewhat reworked hummocky cross stratifications (HCS), flat or undulatory laminations, or 3D ripples (Guillocheau, 1983; Brenchely *et al*., 1986; Guillocheau and Hoffert, 1988; Deynoux *et al*., 1991) by the second wave dominated phase.

As will be shown later storm and wave action dominate processes in the thick bed rock and other massive sandstone beds. However they do not seem to have played a major role in the deposition of the sequences. These are probably mainly generated by gravity flow processes as supported by the following arguments:

1. The laterally continuous aspect of the sequences.
2. The consistent development of internal divisions conforming more or less to the Bouma sequences.
3. The absence of angle of repose cross-beddings.
4. The repetitive aspect of the sequences without fair weather deposit intercalations.

The lower part sediment gravity flows may represent the fore slope deposition of a subaqueous contact fan fed by water streams. The repetitive sequences reflect the episodic pulses of dense sediment laden water streams swept down the fan and may represent the turbidities sequences.

3.2 (Proximal turbidite) glaciomarine facies association "middle unit B"

3.2.1 Description

This unit attains a thickness of about 80m in Kuhlan type locality in the Kuhlan village at Hajjah district. It lies on the lower unit A of Kuhlan Formation, and characterized by the presence of irregular diamictite beds varying in thickness from 2m to 4m. The diamictite is interbedded with overriding deformed beds of alternative sequences of conglomerates, sandstones, siltstone and shale, lying above the polygonal siltstone beds. It also displays thick, massive, reddish, coarse to medium-grained sandstone with scattered dropstones of different sizes and origin. The middle part is made up of alternates of 0.3m to 5m thick fining upward sequences of coarse to medium-grained siliciclastic sandstones including erosional submarine channels (erosional soles). Sedimentologic facies are highly variable, and characterized by the development of wave ripples associated with convolute beddings, planar or wavy beddings and tabular cross beddings. Out of size clasts (dropstones) of various origins (Basement rocks) and sizes (pebbles to boulders) are scattered throughout the unit with no apparent correlation to the nature of the sedimentary structures.

Locally a few meters of medium-grained sandstones with current ripples and flat to wavy parallel laminations, or a very irregular (0.1 - 0.5m) conglomeratic sandstone with dispersed clasts of various origin and sizes (up to 10cm), are intercalated with thick sandstones, diamictites and the fully developed fining upward glacioturbidites sequences. From base to top, a complete sequence displays the following characters:

(i) 30cm to 2m coarse to conglomeratic sandstones and conglomerates with isolated angular to rounded pebbles of various sizes (up to 10cm) and origin (granites, volcanic rocks, gneiss, schist, quartzite, jasper …etc). This horizon which passes progressively into the overlying medium-grained sandstones is generally structureless, but shows in some cases crude horizontal bedding. It is present in the lower part of the glacioturbidites sequence.

(ii) 0.5m to 1m of medium-grained sandstones with defined parallel flat to slightly undulating laminations and some times displaying normal cross beddings.

(iii) About 0.3m to 0.5m of fine grained rippled sandstones show fining upward to shales. This horizon is present frequently but the ripple marks do not appear frequently.

Some fining upward sequences, especially the thinnest, pinch out and others thicken in flat and shallow depressions for a few to ten meters wideth; however, most have rather good extension which exceeds several hundred meters of best exposures.An irregular lenticular horizons of 1-4m thick of massive and stratified diamictite is intercalated with sharp contact within the sequences. It is composed of angular to subrounded various size clasts dispersed in a microconglomreatic sandy-clay matrix. The clasts, 80cm to 1.5m in size, are mainly fragments of Basement rocks (Granite, quartzite, gneiss…etc). The massive sandstone beds, which comprise few skolithos burrows with cruziana trace fossils, have a sharp flat erosional base. They are graded and structure less or show flat undulatory or hummocky laminations. In some places the massive sandstone beds are 1m thick and consists of flat laminations. Most beds of the sandstone show deformations represented by slump contorted structures with disturbed beds of interferences of conglomerates (gravel lags) and sandstone sediments. Deformed sandstone beds including ball and pillow structures sandstone displays a huge size and reaches up to 1m in diameter. Repetitive bed sets of 0.5m to 0.75m thick show an association of combined flow ripples and convolute laminations.

3.2.2 Interpretation

Subaqueous streams of melt water outwash are the proposed origin for the conglomerates locally preserved in the original bounding surface or in submarine channels. The subaqueous streams were coming annually from the melting of glaciers. This interpretation is based on the presence of rough cross stratifications, pebble imbrications, pebble shape and limited lateral extent. The diamictites have been described to be the deposition of lodgment till at the time of glacial entrance in the sea or the drop down of lodgment clasts from the floated icebergs up on argillaceous sandy matrix (Walker, 1984b; Reading, 1986; Deynoux *et al*., 1991; Einsele, 1992; Walker and James, 1998; Crowell, 1999). The faint bedding and clusters of pebbles observed in the diamictite may correspond to shear planes and lodgment which characterized basal tillite (Dretmants, 1969; Boulton, 1970; Reading, 1986; Einsele, 1992; Walker and James, 1998) or debris flow processes which operate in flow tills (Hartshorn, 1958).

The overlying few meters of sandstones with interbedded siltstone and shale beds represent shallow marine deposition, preserved between the underlying erosional surface and the overlying transgressive surface (Dretmants and Kraft, 1987; Nummedal and Swift, 1987; Deynoux *et al*., 1991). The latter surface is overlapped by sandstone bars which are interpreted as inner shelf sand ridges accompanying the shore face retreat of the upper part of the formation. The size of these sand ridges appears exceptional when compared to modern (Swift *et al*., 1978; Swift and Field, 1981; Stubblefield *et al*., 1984) or ancient (Boyles and Scott, 1982; Rice, 1984; Shurr, 1984) models. They have been studied in detail in Kulan–Affar road at Hajjah district and they suggest that the origin is based on:

- Their geometry and inter-relationship.
- The well sorted nature of the sediments.
- The lack of fine-grained deposits (silt or clay).

- The presence of local normal cross-stratifications.
- The nature of sedimentary structures (planar laminations, cut – and – fill structures, swaley and hummocky cross stratifications) which are characteristics of a shallow water high energy environment.

The middle unit of Kuhlan Formation displays analogies with the Bouma sequences as evidenced by:

- Repetition of fining upward sequences.
- Upward succession of massive, parallel laminated, rippled sandstones.
- Good lateral extensions.

However, the occurrences of sediment gravity flows might appear quite surprising at first glance except in the context of glacial environment whose input is evident in the middle part of Kuhlan Formation.

Mechanisms by which sediment gravity flows are settled down have been discussed and applied to relatively deep sea sediments in a great deal of literature (e.g. Bouma, 1964; Carter, 1975; Middleton and Hampton, 1976; Nardin *et al*., 1979; Lowe, 1979, 1982; for references, terminology and classification). Turbidity sequences have also been reported in shallow water environments (Stainly, 1968; Hubert, 1972; Thompson, 1972; Scott, 1975; Homewood, 1983). The association on shelf of such deposits and glaciomarine sediments has long been postulated (Crowell, 1957; Dott, 1961; Winterer, 1964; Hefzen and Hollister, 1964), and ice proximal down slope sedimentation is now accepted as an active process. Mud flows and high to low density currents have been extensively described in recent papers, either in ancient or modern glacial sequences (e.g. Evanson *et al*., 1977; Rust, 1977; Hicock *et al*., 1981; Powell, 1981, 1983; Gazadzick *et al*., 1982; Domack, 1982; Visser, 1983a-b; McCabe *et al*., 1984; Eyles *et al*., 1985). All these resedimentation processes take place when ice-marginal fans, deltas, and other build-ups become unstable from oversteepening due to either: rapid sedimentation, glacier motion or iceberg calving, increased overburden pressure or load, storm wave agitation or earthquakes.

If the mechanisms which caused the coarse to fine sand size sediments of the sequences to settle down are related to sediment gravity flows, the following high density current process could be envisaged according to the terminology of LOWE (1982). The sequences range from coarse to gravelly fully turbulent flow (horizon 1), to a more dilute and laminar sandy flow (horizon 2) with traction suspension deposition shown by flat laminations and occasional rippled cross laminations. However, submarine channels were filled with semi- and unconsolidated sediments which display stratified sandstone and argillaceous sediments. Depressive pressure remained active in the overlying laminated sandstones of horizon 2 where traction carpets are represented by inversely graded micro-conglomerate streaks.

Mechanisms related to debris flows are certainly involved in the deposition of the intercalated diamictite horizon which looks like a tillite, with clasts of various sizes, shapes and origin, floating in a massive and stratified clay-silt-sand matrix. However, as emphasized by Eyles *et al*., (1985), realistic interpretations of diamictite genesis must be preliminarily based on lithofacies relationships and sequence context. The intercalation of a few meters thick tabular body of diamictites within undeformed turbidity sequences is representative of a debris flow in which clasts were supported by strength and buoyancy of sand-clay water fluid.

Several authors described shallow water graded sand beds with a vertical succession of structures that resemble those of deep water turbidites as related to storm effects (Kelling and Mulling, 1975; Brenchely *et al*., 1979; Hamblin and Walker, 1979; Nelson, 1982; Dott and Bourgeois, 1982, 1983; Walker *et al*., 1983; Walker, 1984a). Two phases overlapping in time are recorded in storm deposits: (i) an initial phase of transport and deposition which emplaces the sand on the shelf, and (ii) a second phase during which the sand is reworked by storm waves (Brenchely, 1985). Among others (wind-forced currents and storm-surge ebb currents) turbidity currents have been postulated to be responsible for the initial phase (Hamblin and Walker, 1979; Walker *et al*., 1983; Walker, 1984b). Such currents lead to the formation of Bouma subdivisions which are somewhat reworked hummocky cross stratifications (HCS), flat or undulatory laminations, or 3D ripples (Guillocheau, 1983; Brenchely *et al*., 1986; Guillocheau and Hoffert, 1988; Deynoux *et al*., 1991) by the second wave dominated phase. In the middle part no typical HCS or wave related ripple marks have been found, but the following characteristic may suggest some analogies with the storm sequences as defined by DOTT and Bourgeois (1982, 1983), Walker *et al*. (1983) or Brenchely (1985):

(i) The occasional presence at the erosional sole of apparently non-preferentially oriented gutter-casts or even pod casts.
(ii) The massive and ungraded aspect of some basal coarse horizon 1.
(iii) The frequent undulatory aspect of the lamination of horizon 2.
(iv) The occurrence in some examples of complex polygonal ripples which may represent small scale HCS as described by Guillocheau (1983), Brenchely *et al*. (1986) or Guillocheau and Hoffert (1988).
As will be shown later, storm and wave actions are the dominate processes in the thick bed rock and other massive sandstone beds; however they do not seem to have played a major role in the deposition of the sequences. These are probably mainly generated by gravity flow processes as supported by the following arguments:
(i) The laterally continuous aspect of the sequences.
(ii) The consistent development of internal divisions conforming more or less to the Bouma sequences.
(iii) The absence of angle of repose cross-beddings.
(iv) The repetitive aspect of the sequences without fair weather deposit intercalations.
The middle part sediment gravity flows may represent the fore slope deposition of a subaqueous ice-contact fan fed by melt water streams. The repetitive sequences reflect the episodic pulses of dense sediment laden melt water swept down the fan and may represent “glacioturbidites”. The presence of a more or less proximal land based or seagoing ice margin is indicated by the lone stones (dropstones) dropped in the flat laminated horizons of the “glacioturbidites” and by debris flow intercalations.

3.3 Shallow marine shelf facies association “upper unit C”

3.3.1 Description

Successions of facies types including very thick, massive, reddish yellow to whitish, medium to coarse-grained sandstone were recognized in the upper part of Kuhlan Formation.
It displays sequences of alternates of laminated siltstone/shale successions red in colour present in the lower most part of the upper sequences. The laminated siltstone/shale successions are overlying very thick massive and locally cross-bedded whitish sandstone beds reaching up to 35m in thickness. The contact between the siltstone /shale and the very thick sandstone facies displays an intense horizon of trace fossils of skolithos and cuziana species including burrows. The sequences display characteristic sedimentary structures of wave action and storms in shallow marine conditions. They show changes in colour upwards from reddish drab to whitish colour. They also show lithological transformation from quartz arenite sandstone to calcareous sandstone and later to sandy limestone at the gradational contact with the overlying Amran Group.

3.3.2 Interpretation

The interbeds of sandstones with laminated siltstone/shale represent shallow marine depositions, which are preserved between the underlying erosional surface and the overlying transgressive surface (Demarset and Kraft, 1987; Nummedal and Swift, 1987; Deynoux *et al*., 1991). The later surface is overlapped by very thick sandstone bars which are interpreted as inner shelf sand ridges accompanying the shore face retreat of the upper part of the formation. The sizes of these sand ridges appear exceptional when compared to modern (Swift *et al*., 1978; Swift and Field, 1981; Stubblefield *et al*., 1984) or ancient (Boyles and Scott, 1982; Rice, 1984; Shurr, 1984) models. They have been studied in detail at Kuhlan –Affar road at Hajjah district but they suggest an origin is based on the same criteria as in the case of the Middle Unit B above.
There is an initial phase of transport and deposition which emplaces the sand on the shelf, and a second phase during which the sand is reworked by storm waves (Brenchely, 1985). Such currents lead to the formation of Bouma subdivisions which are somewhat reworked hummocky cross stratifications (HCS), flat or undulatory laminations, or 3D ripples (Guillocheau, 1983; Brenchely *et al*., 1986; Guillocheau and Hoffert, 1988; Deynoux *et al*., 1991) by the second wave dominated phase. In the upper part no typical HCS or wave related ripple marks have been found, but the characteristics similar to those of the Middle Unit B above may suggest some

analogies with the storm sequences as defined by Dott and Bourgeois (1982, 1983), Walker *et al.* (1983) or Brenchely (1985).

4. Depositional environments of kuhlan formation

The different varieties of facies distributes throughout the stratigraphic column of the Kuhlan Formation can be grouped in three units of facies associations, these are:-

4.1 Unit A (distal turbidites) deep shelf environment

This association of facies types including massive and bedded thick sandstone beds, thick fissile shale beds and siltstone beds comprise the sequences of the lower part of Kuhlan Formation. It consists of massive, cross bedded, green, gray to red colour and fine-grained sandstone and pebbly marine sandstones. The sandstones and pebbly sandstone alternates with thick fissile shale beds of 1-3m shows repetitive Bouma turbidity cycles. The sequences fining upwards show gradual change to red colour. These facies types are suggested to be deposited in the deep part of shelf margin (>100m depth).

The sequences represent distal turbidites of deep marine shelf sedimentation and consequently facies association. The deep marine shelf margin comprises developed stages of marine regression starting in the transitional unit between Akbra and Kuhlan Formations. This regression followed major marine transgression affecting the Akbra basin during Late Carboniferous-Permian time. The lower part sequences of Kuhlan Formation comprise the continuous regression of the transitional zone in the Kuhlan sea basin represented by the deep shelf margin (Al-Mashaikie, 2003).

4.2 Unit B (proximal turbidites) glaciomarine shallow shelf marine environment

Association of facies types including massive sandstones, cross-bedded sandstones, pebbly sandstones, rhythmic siltstones, laminated siltstone/shale and deformed siltstone/mudstone, are arranged in repetitive Bouma turbidity cycles. Theses facies alternate with glaciogenic sediments of tillite, stratified diamictite, periglacial marine terminal moraines, submarine outwash, gravel lag and cross-bedded sandy conglomerates figured "glacioturbidites" sequences. The sequences of the middle part of Kuhlan Formation were deposited under the influence of turbidity currents in proximal marine shelf conditions. Annual melting of the huge glaciers led to the formation of strong stream currents reaching the sea basin to form turbidity currents and display submarine channels. The deposition of glaciogenic sediments associates with storm waves, wave action and gravity flow sediments in shallow marine shelf margin. Out size clasts of dropstones, tillite and stratified and massive diamictites reflects important evidences of the glacial effect subjected to the middle part sequences (Walker, 1984a; Reading, 1986; Einsele, 1992; Walker and James, 1998). The characteristic red colour refers to the high oxidation of sediments following an intense rainfall with very wet paleoclimate (Turner, 1980).

4.3 Unit C shallow marine shelf environment

Association of facies including laminated siltstone/shale and the very thick massive and bedded sand bar sandstones formed the upper sequence of Kuhlan Formation. It consists mainly of very thick locally cross-bedded masses, red in the lower most sequence and yellowish white sandstone beds, which are overlying the bedded and laminated red claystone and siltstone/shale laminations. The sequence shows a gradual change in mineralogical composition and colour upwards. The mineralogical composition becomes more calcareous from quartz arenite and later changes to sandy limestone at the gradual contact with overlying Amran Group. The colour becomes more whitish from the red and yellowish white. The massive sandstone has ranges in thickness between 35m and 40m in Kuhlan type section and extended for at least 10-20km. It is thought to be deposited in the shallow shelf margin evident by the presence of the large scale sand bar sandstone (Turner, 1980).This facies association suggests being the start of marine regression which forms the changes of shallow marine sand bar sandstone to very thick sequences of platform limestone beds.

5. Conclusion

Kuhlan Formation comprises an important part of the stratigraphic column in Yemen. It consists of siliciclastic red bed sequences, composed of marine shelf facies varieties. These facies types are grouped in three facies associations, each one comprising a characteristic unit of the lithostartigraphic subdivision.

The first unit of facies association comprises the lower part of the studied formation and composed mainly of massive, cross-bedded and pebbly sandstones. The sequences are arranged in repetitive Bouma turbidity cycles and are thought to be deposited in deep shelf margins. It is evident that the underlying Akbra Formation show marine regression in the transitional unit with Kuhlan Formation.

The second unit of facies association comprises the middle part of the sequence is composed mainly of cyclic repetitions of Bouma turbidity sequences alternating with glaciogenic marine sediments of diamictite, tillite, moraines, submarine outwash, gravel lag and cross-bedded sandy conglomerates. The suggested environment of deposition of this part is thought to be deposited under combination of turbidity currents in a shallow marine shelf conditions. These conditions lead to deposit glacioturbidites sequences under eustatic influence and eustatism of glaciers advancing and retreating.

The third unit of facies association comprises the upper part of the Kuhlan Formation, which is mainly composed of laminated siltstone/shale and sand bar sandstones. The suggested environment of deposition is thought to be deposited under the start of developed marine transgression in the shallow marine shelf margin. The sequences of quartz arenite sandstone are gradually changing upwards to the platform limestone of Amran Group.

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