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Depositional Environments of the Miocene-Pliocene Siliciclastic Succession, Al Rehaili Area, North of Jeddah, Saudi Arabia

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Abstract: A detailed facies and depositional analysis of the Miocene–Pliocene siliciclastic-dominated sequence (ranges from 10 to 35 m thick) of siliciclastic succession below the basalt rocks have been carried out to interpret the depositional pattern, facies and sedimentary depositional environments. This siliciclastic-dominated succession, underlying Harrat Rahat, belonging to the Miocene–Pliocene is exposed at Al-Rehaili area, North Jeddah. Three main depositional units from bottom to top: Unit I, II and III are identified and correlated. These units comprise of gravels/conglomerates, sandstones, siltstones and mudstones. Sandstones below the basaltic rocks of Harrat Rahat generally contain about 30-70 % quartz, 10-50 % rock fragments, 10-20 % feldspar, 15-40 % detrital clay, 2-8 % iron oxides, and minor amounts of other components. Siltstones are distinguished from sandstones by their finer grain sizes of the quartz silt (45-70 % quart and higher proportion of clay (30-55% detrital clay minerals). Mudstones contain about 25-50 % quartz, 40-60 and detrital clay minerals, 2-8 iron oxides, and minor amounts of other components. Based on petrography, components, textures, fabrics, contacts nature, sedimentary structures, stratal geometry, and stratigraphic relationships, ten facies, covering the three depositional units are distinguished representing fluvial to lacustrine depositional conditions.

Keywords: Fluvial, lacustrine, depositional units, grain-size, Sedimentary facies Saudi Arabia.

INTRODUCTION

Non-marine silicilastic succession is present in most of the stratigraphic sequence (e.g. Wright and Marriott, 1993; Shanley and McCabe, 1994) and is controlled by numerous factors including base-level changes, climatic variations, tectonics, sediment calibre and hydrology. Among these factors, base-level variations, syn-depositional tectonics and climate are considered to be the most significant factors that influence the overall fluvial channel architecture and size. Tectonics (uplift or subsidence) and base-level fluctuations are the main controls on the rate of accommodation creation or destruction (Vail et al. 1977; Van Wagoner et al. 1990). Therefore, these factors determine whether fluvial systems incise, aggrade or migrate laterally. Climate change may also have a significant influence on fluvial channel style by affecting the rate and calibre of sediment supply, vegetation cover, precipitation and discharge; however, climate is only rarely considered (Blum and Törnqvist, 2000).

The Miocene-Pliocene fluvial/alluvial-lacustrine successions are exposed in different areas along the coastal plain of the Red Sea; however, they are scattered. In addition, limited studies have been conducted on these exposures. New road cuts in the north-eastern part of Jeddah have exposed several outcrops which allowed some (Ghandour and Hamad, 2013) to study in detail the sequence stratigraphy of the Miocene-Pliocene fluvial/ lacustrine successions in Al Rehaili area. Ghandour and Hamad (2013) have divided the Miocene-Pliocene succession into three sequences. These sequences are composed of four sedimentary facies associations. The facies associations range from very fine to coarse-grained sediments that are deposited within fluvial and lacustrine environments. All these results are based on the analysis of only one outcrop exposed by the road cutting within the area.

Continued road cutting has exposed a few more outcrops within Al Rehaili area. This study examined these new exposures located in the Al Rehaili area. The study area has latitude of 21°25'15" N and longitude 78°00'00" E (Fig. 1). The cumulative thickness of the studied succession is *ca.* 128 m, comprising of very fine-grained mudstone and medium to coarse-grained sandstones with pebble and gravel conglomerates. The main objective of this study is to describe the sedimentary facies, rock types, and petrography to interpret the depositional environments of the Miocene-

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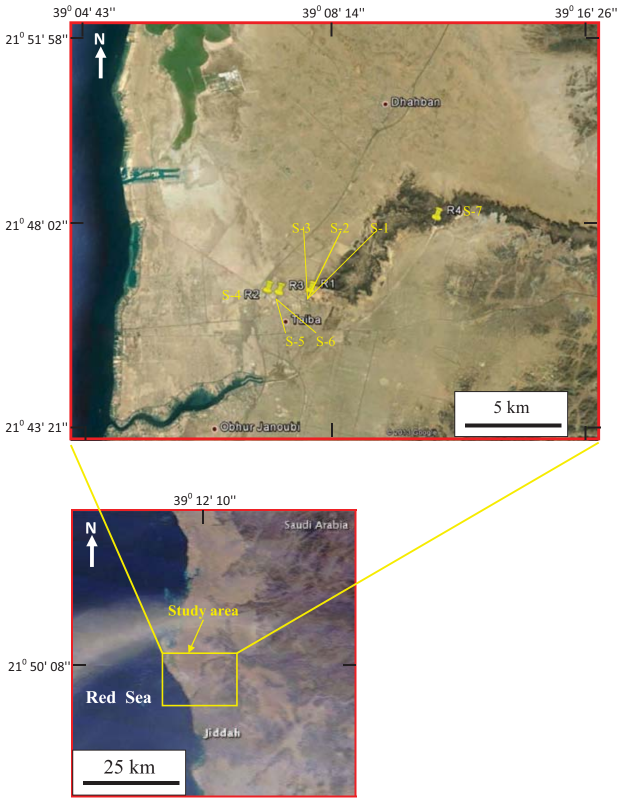


Fig.1. Satellite images shows the study area, with the locations of the measured sections and analyzed samples.

Pliocene succession exposed at Al Rehaili area, north of Jeddah.

GEOLOGICAL SETTING

The Red Sea is considered as a rift basin. The succession within this rift basin can be divided into two major subdivisions: (1) pre-rift sediments represented by continental siliciclastics and fluvial facies, where the oldest deposits are found close to Jeddah (few kilometers to the north) and could be of upper Cretaceous age; and (2) syn-rift sediments which are represented by thick evaporite-clastic series deposited due to invasion of the Mediterranean seas southward into a closed depression.

Local Miocene basaltic lavas within the Red Sea depression are inter-layered with these evaporites and siliciclastics sequences. During the early Pliocene, the Red Sea became part of the regional rift system. Furthermore, there is an unconformity between the evaporite section and the overlying marine oozes, which marks the beginning of drifting. Although the syn-rift units on both sides of the Red Sea are of similar facies, thicknesses, and depositional environments, they have different stratigraphic nomenclatures.

The present study area covers part of the Miocene-Pliocene succession exposed within Al Rehaili area. This succession is covered by the basaltic rocks of Harrat Rahat. The age of Harrat Rahat is very well-known to be 5-11 Ma (Camp, et. al. 1991). As described above, the studied succession is unconformably overlain by Harrat Rahat which has very wide spread basaltic lava that overlies siliciclastic succession. Within Rehaili area, the siliciclastic succession is interpreted to be Bathan Formation by some researchers (e.g. Ghandour and Hamad, 2013; Schmidt and Hadley, 1984; Taj, personal communication). Schmidt and Hadley (1984) studied an equivalent succession (Bathan Formation) along the coastal plain of the Red Sea north of Jeddah and mentioned that the age of the Bathan Formation is between 12 and 15 Ma; however, similar deposits are given different names in other areas along the coastal plain of Red Sea Jeddah Area. For example, the non-marine siliciclastic succession in Usfan area which is exposed few tens of kilometers south-eastern of Al Rehaili area is named Usfan Formation. It is interpreted as lower Tertiary deposits by Khallaf et al. (1980). Khallaf et al. (1980) have suggested that the deposits of Usfan Formation could be extended to Al Rehaili area. Due to the lack of marine fauna, the exact age of these formations cannot be determined and hence a correlation between these both Bathan and Usfan formations cannot be established.

METHODOLOGY

Six columnar sections covering four exposures have been carefully measured, described and sampled (Figs.2 and 3). All the field data such as determination of bed and bed sets, rock types, nature of the contacts, and erosional surfaces have been described. Twenty eight samples covering all the measured columnar sections have been taken (Figs. 4 - 9). The erosional surfaces and soil horizons were traced laterally throughout the study area. Sedimentary facies analysis including the components, textures, fabrics, nature of contact, primary sedimentary structures, stratal geometry, stratigraphic relationships and detailed petrographic analysis have been carried out. The vertical and lateral changes in the sedimentary facies have been determined and used for constructing the correlation columns (Figs. 2 and 3).

Twenty thin-sections representing all the sedimentary facies have been well-prepared and described by using petrographic microscope under both plain polarized, and analyzed (cross-nicole) light to determine the rock types and to predict the maturity of studied beds and succession. Furthermore, the information has been used to the interpret sedimentary facies and thus the depositional environments.

Average modal composition of each sample has been

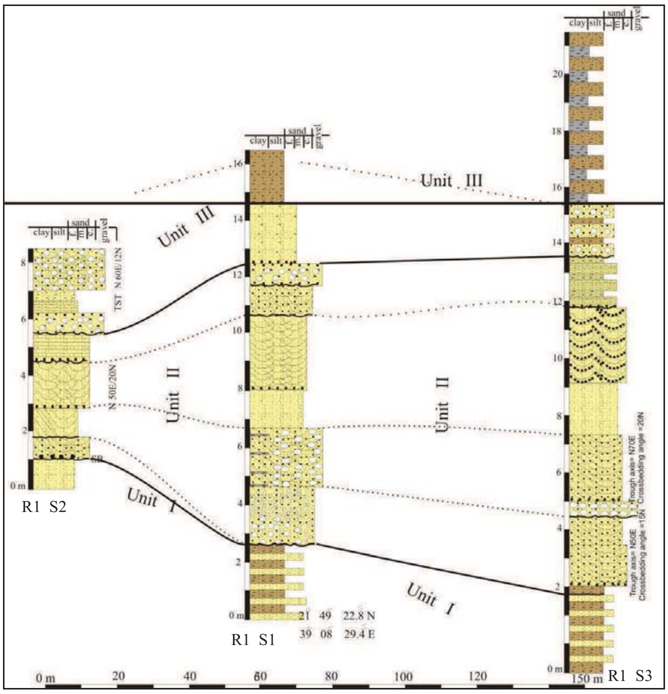


Fig.2. Lateral correlation of the identified three units I, II & III, vertical facies changes of the studied columnar sections.

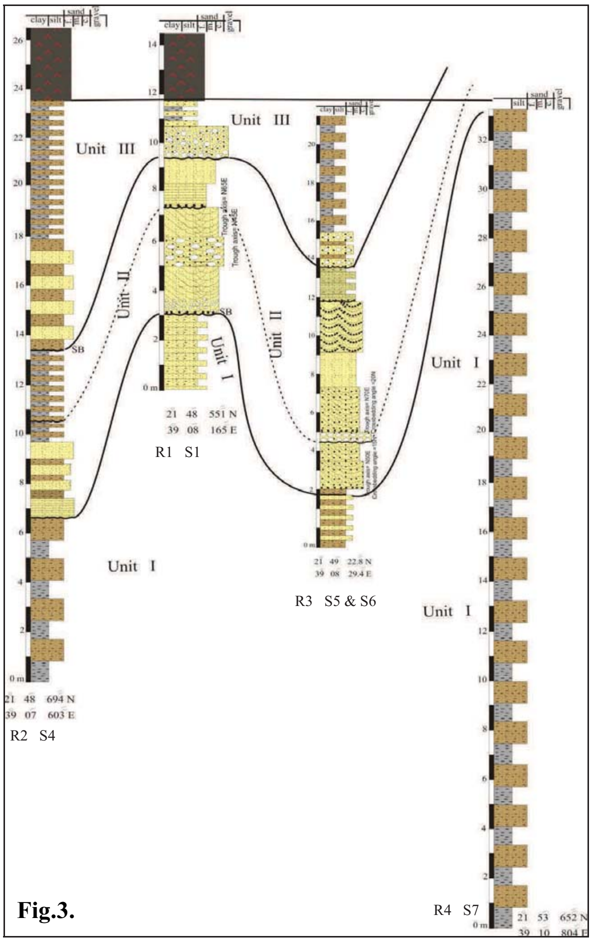


Fig.3. Lateral correlation of the identified three units I, II & III, vertical facies changes of the studied rock units.

determined (Table 1). These modes are determined by making number of systematic traverses within the thin-section and then taking readings on visual estimation in several field views. In addition, the modal point counts of mineral components have been counted directly from the thin-sections (Table 1). These points have been counted for all samples using a click stage and not counting more than 200 points per thin-section in traverses 1 mm apart. Greater accuracy for individual thin-section has been obtained by counting more than 500 points. Percentage estimations of the mineral compositions from thin-sections have been determined by using modal estimation charts. Modal estimation charts are created based on extensive estimates of varying known percentages of filled space within a given area. Further, estimates have been then double checked by counting the points until accuracy is acquired.

RESULTS

Depositional Units

Based on the field analysis, three main depositional units have been identified and correlated throughout the study area. These units are from bottom to top as: Unit I, II and III (Figs. 2 and 3). Unite-I is composed mainly of intercalations of massive and bedded yellowish brown to reddish brown siltstones, shales and very fine, fine- to medium-grained sandstones (Figs. 4, 5, 6, 7 and 9). Towards the east of the study area, this unit is composed totally of shales and siltstones (Fig. 9), while towards the west it is made up of medium to fine-grained sandstones (Figs. 4, 5, 6 and 7). The exposed part of this unit varies from 4- 17 m (Figs. 4, 5, 6 and 7) at the western part of the study are to 35 m (Fig. 9) at the eastern part. Unit I might have been deposited in fresh-water lacustrine environment and was supplied with water and sediments by low-sinuous channels coming from the northeast.

Unite-II consists of large-scale trough and planner cross-bedded conglomeratic/pebbly ill-sorted sandstones with thin siltstones and shale inter-beds with many erosional and channelized surfaces (Figs. 4, 6 and 7). It is overlain and underlain by erosional contacts (paleo-soils) with Unit-III and Unit-I, respectively (Figs. 4 and 6). This unit is exposed only in the western part of the study area and its thickness ranges from 7 to 15 m (Figs. 4, 5, 6 and 7). This unit was

Table 1. Modal analysis of the estimated components in the identified facies.

Facies	Qz (%)	Feld. (%)	R.f. (%)	D.c.m (%)	Ir. ox. (%)
Channel fills sandstone/ gravel (F1)	50	10	15	21	4
Clayey sandstones/ siltstone (F2)	44	8	14	25	8
Bedded medium-grained sandstone (F3)	67	5	9	15	3
Laminated fine to medium-grained sandstone/siltstone (F4)	74	3	10	10	2
Massive siltstone/fine-medium-grained sandstone (F5)	74	5	10	8	2
Massive, blocky, siltstone/clay-rich mudstone (F6)	30	52	6	4	5
Poorly sorted coarse-grained sandstone (F7)	52	10	26	10	4
Thickly bedded massive mudstone (F8)	25	5	5	60	4
Thickly bedded medium to coarse-grained pebbly sandstone (F9)	66	5	15	10	3
Clast supported conglomerate/ pebbly/couply sandstone (F10)	52	5	25	15	2

Qz = Quartz, Feld. = Feldspars, R.f. = Rock fragments
D.c.m.= Detrital clay matrix, Ir. ox. = Iron oxides

deposited more or less by low-sinuous channels coming from the northeast.

Unit-III (Figs. 5, 6, 7 and 8) starts with a base of sandstones (occasionally pebbly/conglomeratic) grading upward to shales and siltstones and occurs only in the western part of the study area (Figs. 5, 6, 7 and 8). It varies in thickness from 4 to 17 m with erosional contacts (occasionally paleo-soils) with the underlying unit (Unit-II) (Figs. 6 and 7). This unit rests uncomfortably under the basalt of Harat Rahat (Figs. 7 and 9). The deposition of Unit-III is started by low-sinuous channel regime which are covered gradually by a phase of prograded fresh-water lacustrine deposits towards the west.

Facies Analysis

Based on facies analysis, ten sedimentary facies within the three described depositional units have been distinguished (Tables 1-2, Figs. 4-9). These sedimentary facies are described below.

Channel Fills Sandstone/gravel Facies (F1)

This facies occurs commonly in depositional unit-II (Figs. 4, 5 and 6) and occasionally in unit-III. The axes of these channels run in NE–SW direction. These channel fills are made up of massive to horizontal bedded and occasionally cross-bedded sandstones with bed sets thickness ranging from 1.5 to 8 cm. Each stack ranges from 0.3 to 0.6 m thick and has a sharp erosional base. These bases are defined by poorly sorted gravels, which vary in grain sizes from granule to boulder and includes granites, other igneous rock fragments, quartz, mud clasts, and others.

In thin section, this facies is composed of rock fragments of igneous and metamorphic rocks, quartz pebble and sand-sized grains and feldspars which are found in silty, clayey and iron oxide matrix. This facies contains about 50 %

Table 2. Facies description and depositional sedimentary environments for the identified facies

Facies	Depositional sedimentary environment
Channel fills sandstone/ gravel (F1)	Multistory channel fills of low sinuosity shallow wadies/streams filled with repeated sheet floods.
Clayey sandstones/ siltstone (F2)	Abandoned channel affected by pedogenic processes
Bedded medium-grained sandstone (F3)	Sand bar of high-energy sandy sheet flood deposits.
Laminated fine to medium-grained sandstone/siltstone (F4)	Sheet floods sedimentation on a low-energy flood plain occasionally interrupted by high-energy floods.
Massive siltstone/fine-medium- grained sandstone (F5)	Fore-sets of a progradational units towards the deeper parts of the fresh water lake.
Massive, blocky, siltstone/clay- rich mudstone (F6)	Paleosols horizons, which indicate sub-aerial erosion.
Poorly sorted coarse-grained sandstone (F7)	Deposited on low areas by sheet flood of ephimeral wadies or temporal braided streams.
Thickly bedded massive mudstone (F8)	Deeper lacustrine sedimentation phase.
Thickly bedded medium to coarse-grained pebbly sandstone (F9)	Deposition by settling from suspension in low-energy fresh water lake.
Clast supported conglomerate/ pebbly/ couply sandstone (F10)	Deposition by traction forming elongated bars in a gravel bed-load fluvial system (mostly braided).

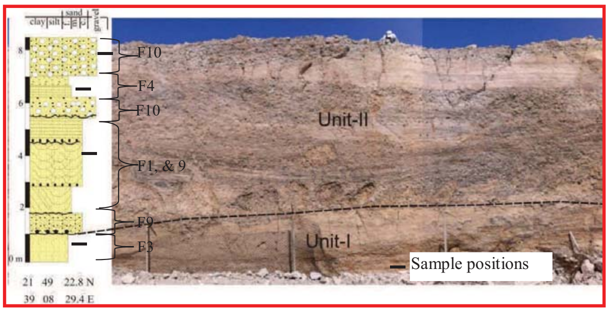


Fig. 4

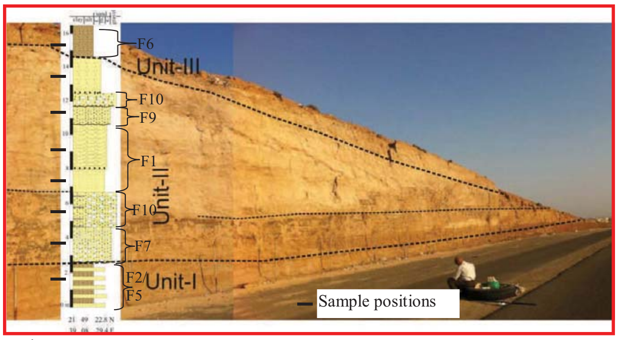


Fig. 5

Figs.(4-6). (4) The lower part of Unit-I, the overlying Unit-II, and facies distribution. It shows measured columnar section with vertical facies changes. The outcrop image is at R1 S-1. **(5)** The three identified units I, II & III, vertical facies changes. It shows the measured columnar section with vertical facies changes. The outcrop image is at R1 S-3. **(6)** The identified three units I, II & III, vertical facies changes, It shows the measured columnar section and vertical facies changes. The outcrop image is at R1 S-2.

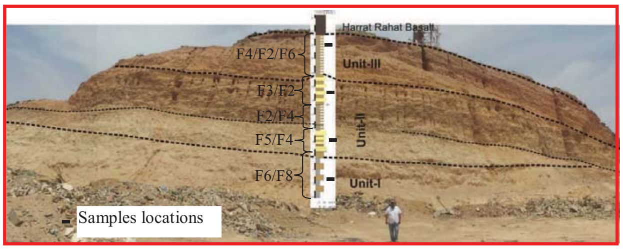
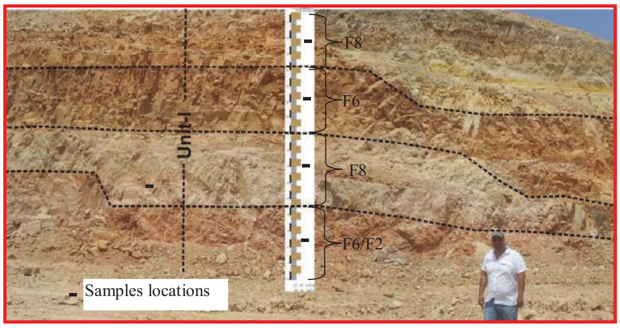


Fig. 7

Fig. 8



Figs.7-9. (7) The three units I, II & III and vertical facies changes. It shows the measured columnar section and vertical facies changes. The outcrop image is at R3 S-5 & S-6. **(8)** Unit-III, the overlying Harrat Rahat basalt and vertical facies changes. The measured columnar section and the outcrop image are at R2 S-4. **(9)** Part of Unit-I, the measured columnar section and vertical facies changes. The columnar section and the outcrop image are at R4 S-7.

quartz, 15 % rock fragments, 10 % feldspar, 21 % detrital clay, 4 % iron oxides, and minor amounts of other components (Fig. 10 and Table 1). The sediment is ill-sorted, the grains have sub-angular to sub-rounded boundaries and pigmented by iron oxide to reddish brown colour. The matrix is made up of silt-sized grains of different composition, detrital clay minerals and iron oxides. The rock fragments are composed of altered metamorphic and igneous grains with common feldspars and mud clasts of different size (0.3 - 5 mm). Many of the quartz grains have a pervasive, ferruginous and hematitic coating. Some of the quartz grains have overgrowth on the grain boundaries. The remaining grains are rock fragments, which are sedimentary and metasedimentary rocks are fine-grained.

The facies is mineralogically immature, which suggest a volcanic source rock. Based on the composition of the sediment, it is classsified as greywacke. This sediment may be very close to its source. This facies represents multistory channel fills of low-sinuosity fluvial stream repeatedly filled with sheet floods.

Clayey Sandstones/siltstone Facies (F2)

This facies commonly occurrs in depositional unit-III (Figs. 7 and 8) and less common in unit I (Figs. 6 and 9) and unit II (Figs. 7 and 8). It is made up of blocky sand-stones, siltstone and dark brown mudstones with roots and mud cracks.

Under microscope, this facies contains about 44 %

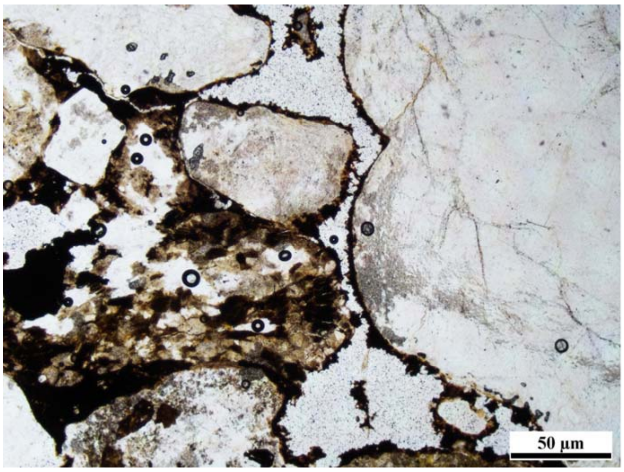


Fig.10. Microphotograph shows channel fills sandstone/gravel facies (F1). It is ill-sorted, sub- angular to sub-rounded grain boundaries and pigmented by iron oxide of reddish brown color.

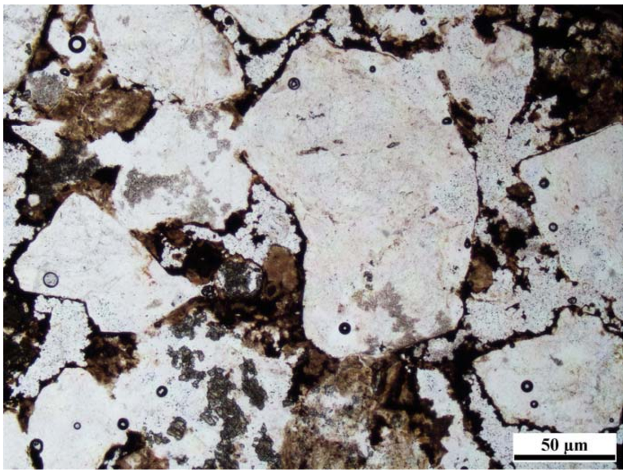


Fig.11. Microphotograph shows bedded medium-grained sandstone facies (F3). it is composed of sandy sized quartz grains, rock fragments within detrital clay and iron oxide matrix The grains range in sizes from 0.4 to 2.0 mm. They have sub-angular to rounded boundaries and moderately sorted.

quartz, 14 % rock fragments, 8 % feldspar, 25% detrital clay, 8 % iron oxides, and minor amounts of other components (Table 1). The grains are ill-sorted, mineralogically immature and have angular to sub-rounded grain boundaries. The matrix between the sand grains is opaque iron oxide and detrital clay minerals. Based on the above information, this facies may represents abandoned channel fill that are affected by pedogenic processes.

Bedded Medium-grained Sandstone Facies (F3)

This facies is very common in unit-III (Fig. 8) and less common in unit-I (Fig. 4). It consists of centimeter-thick sharp-based medium-grained sandstone bed-sets, which display parallel lamination or occasionally massive with irregularly based beds.

In thin sections, it is composed of sand-sized quartz grains, rock fragments within detrital clay and iron oxide matrix. This facies contains about 67 % quartz, 9 % rock fragments, 5% feldspar, 15% detrital clay, 3% iron oxides, and minor amounts of other components (Fig. 11 and Table 1). The grain size ranges from 0.4 to 2.0 mm. These grains have sub-angular to rounded boundaries and moderately sorted. The surface of the grains are coated by thin red-brown rim of iron oxide and most of the quartz are coated with a thin brown rim of hematite. Some of the quartz grains have overgrowths on the grain boundaries. The matrix between the sand grains is opaque iron oxide and detrital clay minerals.

Since the sediment is composed of more than 50% quartz and remaining grains are rock fragments, which are fine-grained sedimentary and metasedimentary rocks, hence the sediment is classified as litharenite. This facies may represent bank deposits along channel margin with sheet flood deposits.

Laminated Fine to Medium-grained Sandstone/siltstone Facies (F4)

It is commonly occurred in Unit-II (Figs. 4 and 7) and Unit-III (Figs. 7 and 8). This facies is composed of centimeters thickly bedded that are characterized by reddish brown fine to medium grained sandstones/ siltstones intercalated with clayey mudstones. Internally, these beds are plane parallel laminated to rarely ripple laminated.

In thin sections, this facies consists of a millimeter scale lamination of sandstones and siltstones (Fig. 12a and b). It is composed of detrital sandy and silty sized quartz grains and rock fragments within clayey and iron oxide matrix. This facies contains about 74 % quartz, 10 % rock fragments, 3% feldspar, 10% detrital clay, 2 % iron oxides (Fig. 12a and b and Table 1). Most of the quartz grains are ill-sorted, sub-angular to sub-rounded and aligned parallel to the lamination (Fig. 12a and b). Many of the quartz grains have a pervasive, ferruginous and hematitic coating whereas some have minor authigenic overgrowths. Most of the grains have sutured contacts, which implies that compaction between the grains had occurred. The matrix between the sand and silt grains contains opaque iron oxide and detrital clay minerals. This facies is interpreted as alternating of sheet flood sediments and flood plain that are occasionally interrupted by high-energy floods.

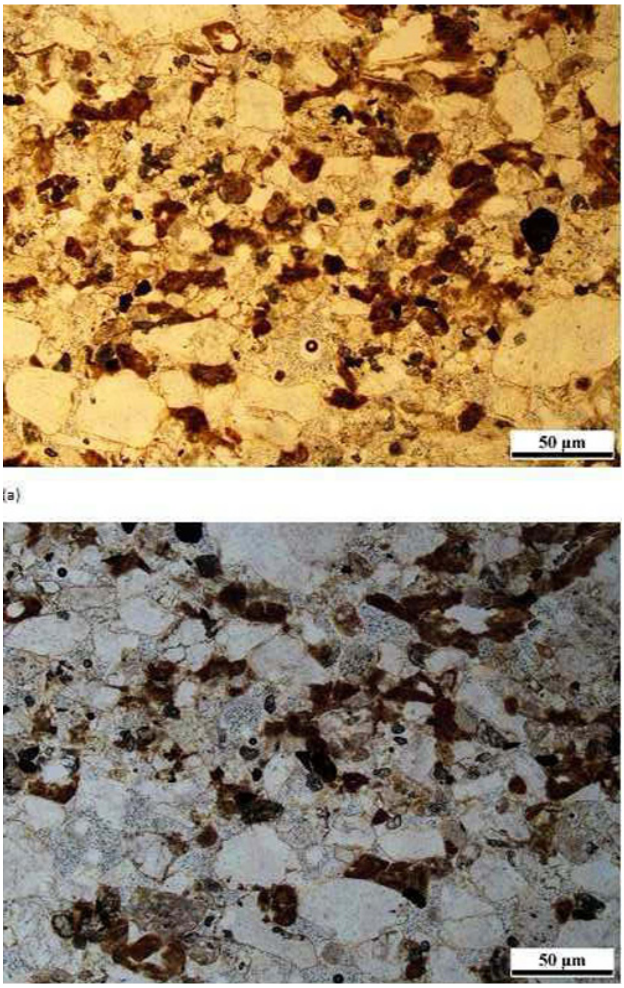


Fig.12. Microphotograph shows laminated fine to medium-grained sandstone/siltstone facies (F4). Quartz grains are ill-sorted, sub-angular to sub-rounded and aligned parallel to the lamination, (a) at R1 S-2 location), (b) at R3 S-6. location.

Massive Siltstone/Fine to Medium-grained Sandstone Facies (F5)

This facies is common in unit-I (Figs. 5 and 6) and less common in unit-II (Fig. 6) and unit-III (Fig. 8). It varies in thickness from 0.3 to 1.5 m and is represented by reddish brown siltstone and fine to medium-grained sandstone that are characterized by plane parallel lamination.

In thin section, it is composed of very fine to fine-grained sandstone/siltstone with grain sizes that are mostly less than 0.25 mm. This facies consists mostly of detrital quartz grains and fine-grained rock fragments within a matrix of clay minerals, finer quartz grains and iron oxides. This facies contains about 74 % quartz, 10 % rock fragments, 5% feldspar, 8% detrital clay, 2 % iron oxides, and minor amounts of other components (Fig. 13a and b and Table 1). Quartz grains are angular to sub-rounded that are mostly single crystals and ill-sorted. Some of the quartz grains have overgrowths on the grain boundaries. Rock fragments are mainly of shale with abundant clay minerals (Fig. 13a and b). The feldspars in plain polarized light (PPL) has cloudly appearance due to altration. The surface of the grains are coated by thin red-brown rim of iron oxide and and most of the quartz are coated with a thin brown rim of hematite. The matrix between the sand grains contains opaque iron oxide and detrital clay minerals.

Since the sediment has more than 75% quartz with the remaining grains which are rock fragments that are of fine-grained sedimentary and metasedimentary rocks, this sediment is called as sub-litharenite. It is mineralogically immature, which suggest a volcanic source rock that would be very close to its source. This facies represents foresets of a progradational units towards the deeper parts

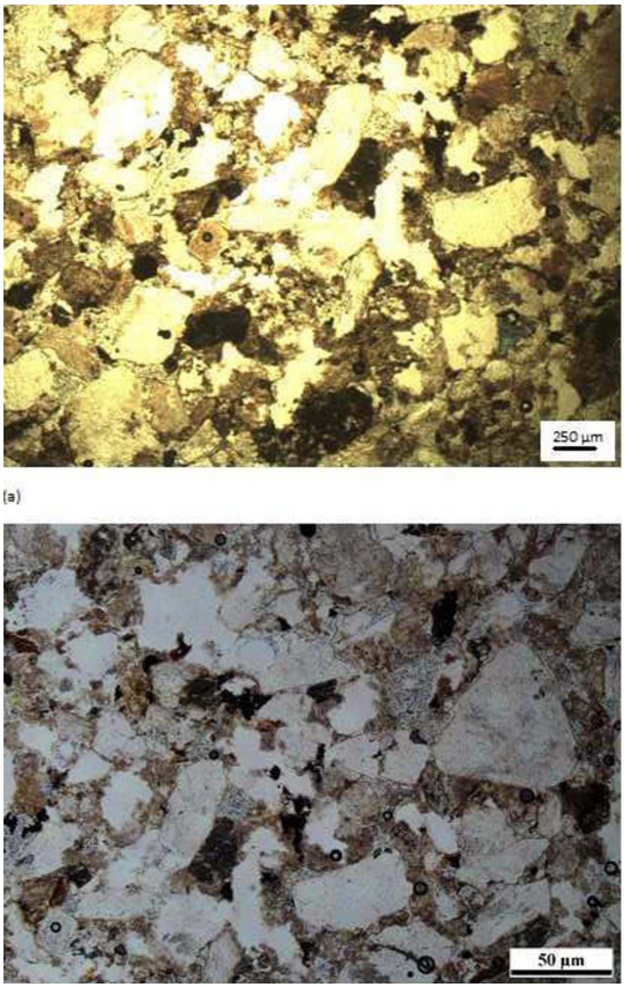


Fig.13. Microphotograph shows massive siltstone/fine to medium-grained sandstone facies (F5). Quartz grains are angular to sub-rounded, ill-sorted which are mostly single crystals, (a) at R1 S-1 location), (b) at R3 S-2 location.

of the fresh water lake and sometimes influenced by storm waves.

Massive, Blocky, Siltstone/clay-rich Mudstone Facies (F6)

This facies commonly occurred in unit-III (Figs. 5, 6, 7 and 8) and less commonly in unit-I (Figs. 7 and 9). The thickness of the beds varies greatly and occasionally disappear (mostly in the northwards) due to effect of erosion of the overlying strata. It is composed of blocky, sharp-based, reddish brown clayey mudstones and massive siltstone. This facies contains about 30 % quartz silt, 6 % rock fragments, 4% feldspar, 52% detrital clay, 8 % iron oxides, and minor amounts of other components (Table 1). It represents paleosols horizons, which indicate sub-aerial erosion.

Poorly Sorted Coarse-grained Sandstone Facies (F7)

This facies occurs commonly in unit-II (Figs. 5 and 6). This facies consists of massive to horizontal stratified, poorly sorted coarse-grained sandstones with decreasing bed thickness and grain size upward.

In thin section, this facies consists of quartz, rock fragments and feldspar grains within detrital clay minerals and iron oxide matrix. This facies contains about 52 % quartz, 23 % rock fragments, 10 % feldspar, 10% detrital clay, 4 % iron oxides, and minor amounts of other components (Fig. 14 and Table 1). The grains are ill-sorted, with grain sizes ranging from 0.2 to 2.0 mm and have angular to sub-rounded grain boundaries. Quartz grains alone are very poorly sorted and include both mono-crystalline and polycrystalline forms. Many of the quartz grains have overgrowths on the grain boundaries and are rimmed by thin red-brown iron oxides as well as coated with a thin brown rim of iron oxides. The rock fragments are of different types, including meta-sediments, igneous, and shale clasts. These rock fragments vary greatly in grain size from 2.0 mm down to 0.1 mm and are commonly contain silt-sized matrix particles. They are of polymectic origin. This facies is mineralogically immature which suggest a volcanic source which is very close. This facies might be deposited on low areas by sheet flood of ephimeral wadies.

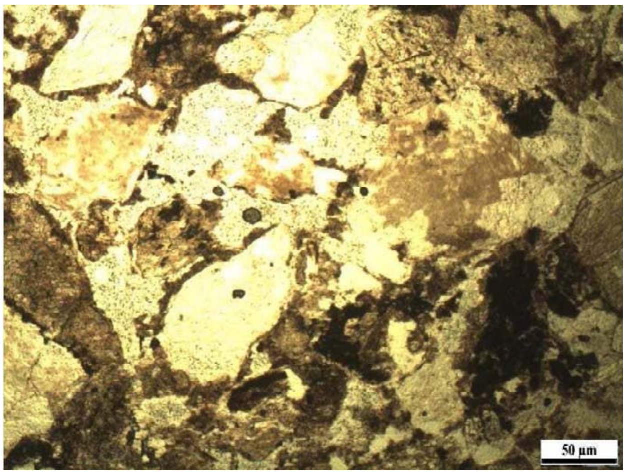


Fig.14. Microphotograph shows poorly sorted coarse-grained sandstone facies (F7). Quartz grains have overgrowthes on the grain boundaries and picked out by thin red-brown rim of iron oxides and as well as coated with a thin brown rime of iron oxides.

Thickly Bedded Massive Mudstone Facies (F8)

This facies is restricted to unit-I and it forms the vast majority of this depositional unit (Figs. 7 and 9). It consists of massive, yellowish brown, clay-rich mudstone. This facies contains about 25 % quartz silt, 5 % rock fragments, 5 % feldspar, 60 % detrital clay, 4 % iron oxides, and minor amounts of other components (Table 1). This facies represents deeper lacustrine sedimentation phase.

Thickly Bedded Medium to Coarse-grained Pebbly Sandstone Facies (F9)

This facies occurs commonly in unit-II (Figs. 4, 5 and 6). It consists of fining-upward medium to course-grained sandstones with abundant mud clasts and quartz pebbles. This facies is characterized by subaerial exposure features such as desiccation cracks, root structures and red beds.

Under petrographic microscope, this facies consists of ill-sorted, medium to coarse grained sand and occasionally pebble sizes, with sub-rounded boundaries. It is made up of quartz, rock fragments, feldspars within detrital clay and iron oxide matrix. This facies contains about 66 % quartz silt, 15 % rock fragments, 5 % feldspar, 10 % detrital clay, 3 % iron oxides, and minor amounts of other components (Fig. 15 and Table 1). The surface of the grains are having a thin red-brown rim of iron oxide and most of the quartz grains are coated with a thin brown rime of iron oxides. Some of the quartz grains have overgrowths on the grain boundaries. The feldspars are seen as cloudy spots in PPL due to patchy alteration of feldspar. Rock fragments are composed of metamorphic rock fragments and shale clasts with abundant clay minerals. The sediment is poorly to modetrely sorted. The matrix between the sand grains contains opaque iron oxide and detrital clay minerals. The sediment of this facies is interperted as Litharenite. It consists mainly of igneous rock fragments which are mineralogically immature sediment that are of adjacent volcanic source rock. This facies represents deposition

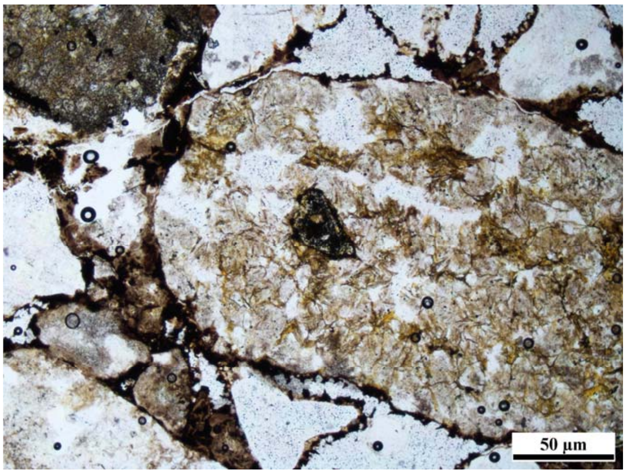


Fig.15. Microphotograph shows thickly bedded medium to coarse-grained pebbly sandstone facies (F9. It is made up of quartz, rock fragments, feldspars within detrital clay and iron oxide matrix.

by settling from suspension in low-energy fresh water lake, occasionally interrupted by storm waves.

Clast Supported Conglomerate/pebbly/couply Sandstone Facies (F10)

This facies is restricted to Unit II (Figs. 4, 5 and 6). The facies consists of matrix to clast-supported and poorly sorted granule to cobble grade conglomerate (clast sizes up to 25 cm). These conglomerates are inter-bedded with massive, poorly sorted coarse-grained sandstones with scattered pebbles. The fragments and clasts are elongate to spherical, sub-rounded to rounded, and mostly derived by the erosion of granite, quartzite and basic igneous rocks.

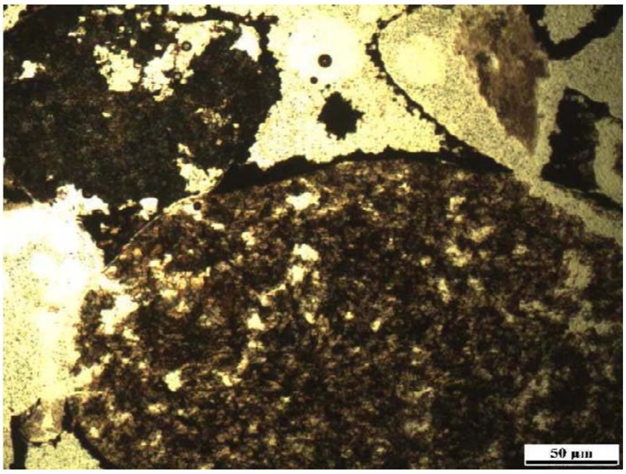


Fig.16. Microphotograph shows clast supported conglomerate/pebbly/couply sandstone facies (F10). It is composed of couple, pebble and sandy size grains of different compositions. The grains are polymectic and are made up of variable rock fragments, quartz and feldspars in silty and clayey and iron oxide matrix.

In thin section, this facies is composed of cobble, pebble and sandy size grains of different compositions. These grains are polymectic and are made up of variable rock fragments, quartz and feldspars in silty and clayey and iron oxide matrix. This facies contains about 52 % quartz, 25 % rock fragments, 5 % feldspar, 15 % detrital clay, 2 % iron oxides, and minor amounts of other components (Fig. 16 and Table 1). Quartz grains include mono-crystalline and polycrystalline grains with corroded boundaries. These grains have a thin red-brown rim of iron oxides as well as coated with a thin brown rim of iron oxides. Some of the quartz grains have overgrowthes on the grain boundaries. The grains of the sediment are ill-sorted, with angular to sub-rounded boundaries. The sediment has many rock fragments that are of different types including larger fragments of meta-sediments, igneous rocks and shale with abundant clay minerals. The matrix is made up of silty sized quartz, rock fragments, altered feldspars, detrital clay minerals and iron oxides. In some places, the matrix contains sub-angular to sub-rounded quartz grains set in iron oxide-rich clayey matrix. The sediment is mineralogically immature, which suggest adjacent volcanic source. This facies may represent channel fill (wadi) deposits that are transported by traction.

INTERPRETATION AND DISCUSSION

The studied Miocene-Pliocene siliciclastic sediments contain three well differentiated continental sedimentary facies reflecting deposition in fluvio-lacustrine setting. The grain size analysis, the vertical and lateral distribution of these facies enables to infer the depositional environments prevailed during sedimentation. The style of sedimentation, and vertical and lateral facies changes pattern seem to be mainly controlled by basin tectonics, sediment supply, fluvial/lacustrine hydraulic regime and climatic changes of the Red Sea basin.

In the study area, the channelized trough and planner cross-bedded units, the presence of features indicating soil formation at several levels and the total absence of marine influence suggest deposition under non-marine setting. The multi-storey character separated by erosional surfaces, indicate a multi-channel river system of low-sinuous channel/wadies (Costello and Walker, 1972; Miall, 1996). They are interpreted as ephemeral streams as evidenced by the presence of several erosional contacts between beds and cross-bedded units, parallel bedding and flash flood deposits which are commonly described in modern and ancient ephemeral streams (Abdullatif, 1989; Reid and Frostick, 1997). The dominance of vertically accreted sand bodies with decrease in grain size and thickness upward suggest that channels were of straight to low sinuosity and aggraded vertically through time due to rapid sedimentation. The massive to horizontal stratification with normal grading suggests sheet flood deposition under fluvial/lacustrine conditions.

The lower depositional unit (unit-I) is incomplete; the basal boundary is not observed and the exposed part attains a thickness of 25 m consisting of fine grained sandstones and shales. The top of this unit is defined red paleosols horizon. This unit seems to be deposited in quite fresh-water lacustrine conditions with the great thickness towards the lake center, (eastern part of the study area) and is devoid of any marine influence.

The middle depositional unit of the studied sequence (unit-II) comprises yellowish white massive clayey and silty sandstone; thinly laminated sandstone; massive gravely/ sandstone/conglomerates; thinly bedded, pebbly at the base, fining-upward, occasionally laminated and sometimes planner cross-bedded sandstone, channelized, large-scale, trough cross-bedded sandstone, pebbly at the base, of low-sinuous channels, yellowish white, large-scale, planner/ trough cross-bedded, fine to medium-grained sandstone with sharp erosional contact, gravelly at the base; thick bedded tan-coloured massive medium to coarse-grained sandstones contain pebble-sized mud and quartz clasts horizontal bedding to cross-stratified; vertically stacked sand-packages with upward-concave basal boundaries locally defined by concentrations of poorly sorted gravels, sandstones with bed thickness varying from 7 to 25 cm; and reddish brown clay-rich mudstones, massive, blocky; yellowish brown to tan-coloured thick bedded massive mudstones. The facies of this unit seem to be deposited in low-sinuous channels system/wadies of high energy with intermittent flood.

The upper depositional unit (unit-III) is unconformably underlies the basalt of Harrat Rahat and is made up of reddish brown, fine-grained, hematitic shales and clays; gravelly reddish brown sandstone and siltstone; yellowish white, thinly-bedded and laminated siltstone and sandstone; fine-grained dark brown sandstone and siltstone/ shales with pillar injection structure; reddish brown, weathered siltstone and claystone; pebbly, and coupley conglomeratic sandstone/ siltstone; yellowish white, massive sandstone with gradational contact; thinly bedded/laminated medium to fine-grained sandstone and siltstone; reddish brown, hematitic, intensely weathered claystone and siltstone; clayey siltstone and fine-grained, reddish brown sandstone; grey to yellowish white, massive, clayey siltstone and mudstone; massive, reddish brown fine-grained sandstone and siltstone; and reddish brown to yellowish siltstone and claystone. The facies of this unit seem to be deposited during later phase of prograded fresh-water lacustrine regime.

Depositional History

The depositional history of the studied area is affected by three depositional regimes as inferred from facies distribution, sediment texture, grain size, spatial distribution of depositional units and stratigraphic relationships.

The First Regime

The first regime is represents lacustrine deposits (unit-I) with fluvial affinities (unit-II) with fluvial deposits located on the high land areas and lacustrine deposits dominate in the topographic depression and low land areas. There is a great difficulty to determine the stratigraphic relationship between the two sub-regimes, whether they were contemporaneous or succeeded each other. The lacustrine sub-regime is dominated by F8 and F6 whereas the other fluvial sub-regime is dominated by F2, F3 and F5. The considerable thickness of F8 of unit-I means that most of fine-grained sediments passed to more distal parts of the fresh water lake. By passing time, the topography was leveled, where the river gradients and hydraulic regime decreased, which is represented by abrupt down-dip transition into sandstone facies and then grades into lacustrine facies (F8 and F6). The high rate of sediment supply and the low gradient of the lake margins suggest the formation of fresh water lake. The presence of reddish brown beds of F2 between beds and bed-sets of F8 and F6 and the development of paleosols suggests change in climate from semi-arid to arid conditions.

The Second Regime

The second regime of depositional history is represented by a change in the depositional regime from fluvio-lacustrine into a wadies/ low-sinuous channels of fluvial regime, which is represented by depositional unit-II. F10 (clast/matrix supported conglomerate/pebbly/ couply sandstones), F9 (thickly bedded medium to coarse-grained pebbly sandstone), F1 (vertically stacked channel fills sandstone/ gravel) and F7 (poorly sorted coarse-grained sandstone) dominate this regime. This fluvial regime had supply of sediments from several and variable catchment areas. It could be explained by tectonic rearrangement of the drainage system in response to renewed uplift along the basin bounded structural elements. This stage characterized by bed-load fluvial wadies/low-sinuous channels streams with intermittent flows and discharge conditions, which is documented by coarse texture, poor sorting, local clasts/

rock fragments imbrications, absence of any marine influence, fining-upward and down-dip decrease in grain size. Planar and trough cross-bedded conglomerate/gravelly sandstone (F10, F9 and F1) are attributed to deposition in low-sinuous channels gravel/sand bars of the river in the shallow reaches under high and fluctuated sediment discharge rates, whereas variable texture within cross sets may be related to variations in sorting resulting from changing hydraulic conditions and gravel clast over-passing. The clast/matrix-supported conglomerate suggests contemporaneous transport of sand and gravel.

The Third Regime

The third regime of the depositional history is represented by fluvial stage with lacustrine affinities and is dominated by depositional unit-III. F5 (massive siltstone/ fine to medium-grained sandstone), F6 (massive, blocky, siltstone/clay-rich mudstone facies), F4 (laminated fine to medium-grained sandstone/siltstone facies), F3 (horizontally bedded medium-grained sandstone) and F2 (clayey sandstones/siltstone) constitute the main facies types of this stage. This stage was deposited under fluvial conditions and this is documented by the presence of several soil horizons, absence of any marine affinities and channelized bases overlain by coarse gravels. The sheet flood deposition under upper flow regime conditions is represented by massive to horizontal normal bedding. The multi-storey sand bodies separated by erosional surfaces, indicate a multi-channel river system of shallow low-sinuous ephemeral channels. The low-sinuous nature of the streams is documented by dominance of vertically accreted sand bodies with decrease in thickness upward.

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