FACIES AND DEPOSITIONAL ENVIRONMENTS OF INJANA FORMATION IN ZAWITA, AMADIA AND ZAKHO AREAS, NORTHERN IRAQ

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Key words: Injana Formation, Facies analysis, Fluvial architectural elements, Meandering river, Depositional environment, Iraq

ABSTRACT

This study deals with facies analysis and depositional environments of Injana Formation (Upper Miocene) in Zawita, Amadiya and Zakho areas. The lower part of the formation at Zakho and Zawita comprises reddish brown mudstone and greenish grey marl representing mudflats (transitional environments). At Amadiya logged succession some coarsening upwards successions are recorded at the lower part representing deltaic environment. The upper part, which is the major part, consists principally of repeated fining-upwards succession nested above each other in a general coarsening upwards in the sand fraction. The Injana Formation comprises seven lithofacies which form eight facies associations. Mudflats and deltaic facies association represent the transitional environments and are of relatively limited thickness and restricted to the lower part only of the formation. Channel floor, point bar, chute and chute bars, abandoned channel, crevasse splay and interchannel floodbasin facies associations represent the high-sinuosity stream (meandering river) forming most of the upper part of the logged successions.

The fining-upwards succession starts with a scour surface at the base of current bedded fine to coarse sandstone with occasional intraformational conglomerates followed by mudstone. In the logged successions, five basic architectural elements are identified: Downstream accretion, Lateral accretion, Floodplain fines, Crevasse splay and Abandoned channel elements. Facies analysis revealed that the upper part of the Injana Formation represents fluviatile deposits basically meandering river system (high – sinuosity streams).

السحنات والبيئات الترسيبية لتكوين إنجانة في منطقة زاويتة والعمادية وزاخو، شمالي العراق

مازن يوسف تمر أغا و نور أنس سلمان

المستخلص

تمثل الدراسه الحاليه تحليل السحنات وبيئات ترسيب تكوين انجانه (المايوسين الأعلى) في المنطقة المحصورة بين زاويته والعماديه وزاخو. يتألف الجزء الاسفل من التكوين في منطقتي زاخو وزاويته من حجر طيني ذا لون بني محمر وصلصال رمادي مخضر يمثل مسطحات طينيه (بيئات انتقالية)، اما في منطقة العماديه يمثل جزء من التتابع تخشن نحو الأعلى وذلك يمثل بيئة دلتيه. يتكون معظم الجزء الاعلى من تكرار تتابع تنعم نحو الأعلى.

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يتألف تكوين انجانه من سبع سحنات صخريه تشكل ثماني مترافقات سحنيه وتمثل هذه المترافقات السحنيه مسطحات دلتيه وهي محدودة الانتشار نسبيا ومحصورة في الجزء الأسفل من تكوين إنجانه فقط، في حين تمثل المترافقات السحنيه الأخرى قاع القناة وحاجز القناة وأشرطة شلال والقناة المهجورة والأخاديد المتباعده والأحواض الفيضيه بين القنوات بيئه نهريه التوائيه ذات مجرى عالي التعرج والذي يشمل الجزء الرئيسي العلوي من التتابع. يبدأ تتابع التنعم نحو الأعلى بسطح تعروي يليه تطبقات الحجر الرملي الناعم والخشن مع احتمالية ترافق مدملكات داخليه.

لقد تم تسجيل خمسة عناصر بنيويه وهي نمو بأتجاه مجرى النهر، نمو جانبي لمجرى النهر، السهول الفيضيه المتأخرة، قطوعات في جانب النهر والقناة المهجورة. أظهر تحليل السحنات الصخريه ان الجزء العلوي من تكوين إنجانه يتمثل بترسبات نهريه وبشكل أساسي أنظمة أنهار التوائيه ذات تعرجات عالية.

INTRODUCTION

Injana Formation (previously called Upper Fars Formation) marks the beginning of the molasse deposits formed during the Alpine Orogeny, when the continent – continent collision of the Arabian with the Anatolion and Iranian microcontinents took place (Beydoun, 1993). It extends as a sheet south of the Taurus and southwest of the Zagros Mountains. It is widely exposed in Iraq. Several studies are carried out concerning its depositional environment, some are based on granulometric analysis such as Gayara (1976) and Al-Samarrai (1978) and others are based on facies analysis such as Al-Banna (1982) and Kurukji (1989). The depositional environment of the Injana Formation is controversial as some believe that it is marine (Al-Ansari, 1972 and Al-Samarrai 1978) while others believe that it is fluvial (Gayara, 1976). However studies based on facies analysis showed that its lower part is transitional whereas its upper part is fluvial (Basi, 1973 and Al-Banna, 1982).

The aim of this study is to establish the depositional environment of Injana Formation at Zawita, Amadiya and Zakho areas. This can be carried out by facies analysis and architecture facies association.

Lithofacies and depositional environment of Injana Formation (Upper Miocene) are logged in three areas in northern Iraq. These logged successions are located in: Zawita (43° 09' 50" E, 36° 56' 17" N) located on the northern limb of Zawita syncline (i.e. the southern limb of Rabatki anticline) along the road from Dohuk to Sarsang (western side of the road), Amadiya (43° 31' 55" E, 37° 03' 26" N) located on the northern limb of Gara anticline at Geli Derish valley and Zakho (42° 39' 25" E, 37° 05' 20" N) located on the northern limb of Bekhair anticline along the Dohuk – Zakho road (western side of the road) (Fig.1). Other isolated outcrops (incomplete) are visited to show certain diagnostic features such as Ashawa outcrop.

METHODS AND SAMPLING

Thicknesses of the logged successions are 140 metres at Zawita, 354 metres at Zakho and 363 metres at Amadiya. The research incorporates field description of three successions in detail for their lithology, contact, sedimentary structures and facies.

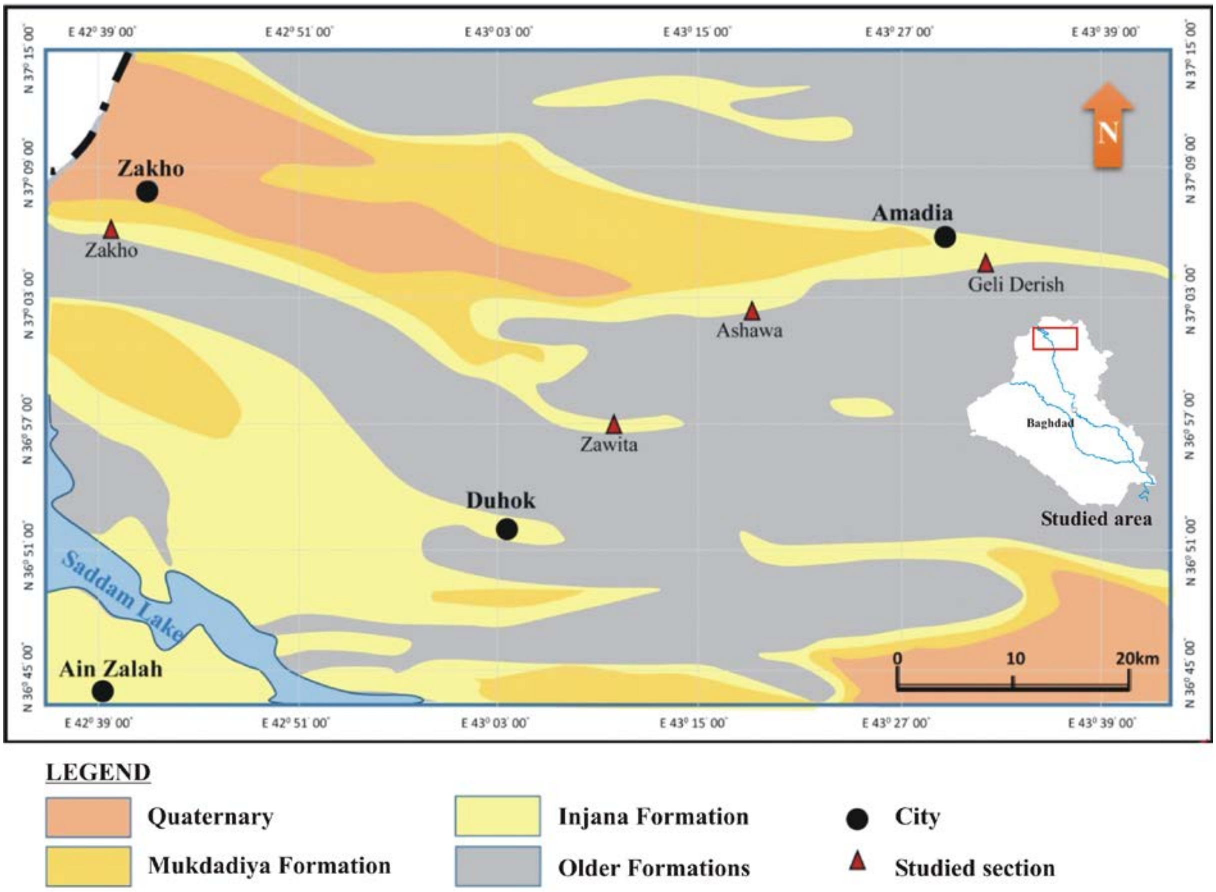

Fig.1: Geological and location map

GEOLOGICAL SETTING

Tectonostratigraphic Megasequence Arabian Plate 11 (Latest Eocene to Present Day) has lasted 34 m.y. and is defined as the package of sediments lying between the unconformity marking both the onset of Red Sea rifting (Beydoun and Sikander, 1992) and the first continent-continent collision between Arabia and Eurasia (Beydoun, 1993; Goff *et al*., 1995), and the present day topographic surface. The Tectonostratigraphic Megasequence comprises the Zagros foreland basin sediments deposited following inversion and erosion of the earlier northeast passive and active margins, as well as Red Sea rift sediments deposited following thermal uplift, doming and rifting along the length of the Red Sea axis. This Tectonostratigraphic Megasequence thus represents the recent Foreland Basin history of the Arabian Plate, with sediments first infilling the long narrow Zagros foredeep, and then prograding southeastwards down the foredeep (Sharlend *et al*., 2001).

The lower contact of the formation with the underlying Fatha Formation (previously called the Lower Fars Formation) is conformable, placed in the field at the top of the uppermost limestone horizon of the Fatha Formation which is overlain by a thick red and subordinate grey mudrock beds. The upper contact of the formation with the Mukdadiya Formation (previously called the Lower Bakhtiari Formation) is transitional; its upper limit is marked by the first consistent appearance of gravel in sandstone.

In Late Miocene – Pliocene time, major thrusting occurred during collision of the Neo-Tethyan terranes and the Sanandaj – Sirjan Zone with the Arabian Plate. This event resulted in the uplift of the High Folded Zone, Northern Thrust Zone, NE parts of the Balmbo – Tanjero Zone and Mesopotamia Zone. A major foredeep formed in the Rutba – Jazira and Salman Zones is uplifted. During the Late Miocene and especially the Pliocene, the High Folded Zone was uplifted with increasing intensity. The products of erosion are deposited in the nearby molasse basin characterized by the conglomerates of the Bai Hassan (previously named Upper Bakhtiari) Formation (Fig.1). In the SW the uplifted Stable Shelf was the source of the terrigenous clastics deposit to the NE of the Euphrates Boundary Fault (Dibdibba Formation) (Jassim and Buday in Jassim and Goff, 2006).

LITHOFACIES

Seven lithofacies are recognized in the Injana Formation at the logged successions, namely: Intraformational Conglomerate, Plane-bedded sandstone, Trough cross-bedded sandstone, Planar cross-bedded sandstone, Cross-laminated sandstone, Interlayerd siltstone/ sandstone and Mudrocks Lithofacies.

- **Intraformational conglomerate lithofacies**

Intraformational conglomerate lithofacies is composed of gravel which is mostly mudclasts reworked from the nearby sediments. The thickness of a single layer ranges from a decimetre to about 50 cm. The lower contact is irregular and sharp surface whereas the upper contact is gradational. The size of the gravel ranges from 1 cm to 8 cm. Mudclasts are usually spherical, subspherical or flat. It shows open-work texture (Fig.2).

Such lithofacies is deposited at the bottom of the channel as lag deposit whether fluvial or deltaic environments. In this study, the authors believe that this lithofacies is formed by river currents when they are in the higher runoff system. The mud balls formed on the river banks originally and in particular on the natural levee as mud cracks during drought forming fragments and the resulting fragments roll to settle at base of the channel as channel lag. This lithofacies is the beginning of a new rock cycle and occurs over a scour surface which is located above the older thick mudstone in the logged successions.

- **Plane-bedded sandstone lithofacies**

Plane-bedded sandstone lithofacies is composed of medium- and fine-grained sandstones. Thickness of this lithofacies ranges from 4 m to 10 m. The sandstone beds are separated by sharp erosional surface. A bed of mudstone may sometimes separate the sandstone beds. Thickness of the mudstone does not exceed 10 cm. Parting lineation is commonly found on the beds surface, (Fig.3).

This lithofacies commonly overlies the channel lag deposits. Plane-bedded sandstone lithofacies can be formed under several hydrological controls and with varied bedloads. It can be formed by a current velocity below the critical velocity of ripple formation (Bogardi, 1965, and Guy *et al*., 1966). Evenly laminated sands can also be produced in the plane-bed phase of a high flow regime (Allen, 1964, and Simon *et al*., 1965). The parting lineation is associated with the lithofacies in the high flow regime (Reineck and Singh, 1973). This lithofacies is considered to present deposition in fluvial channel, a distributary mouth bar or a distributary channel, although horizontally laminated fine sand and silt with clay is believed to be formed at low-current velocity and therefore represents a distal bar environment (see the photo of Fig.11 later).

Fig.2: Intraformational conglomerate lithofacies, with scoured surface of the base followed by mudclasts "floating" in sandstone at Ashawa outcrop

Fig.3: Plane-bedded sandstone lithofacies indicated by arrow (↑), at Amadiya logged succession

- **Trough cross-bedded sandstone lithofacies**

Trough cross-bedded sandstone lithofacies is composed of fine- to coarse-grained, moderately- to poorly-sorted sandstone. Sets of trough-cross beds vary in thickness from 15 cm to 30 cm. Set thickness is generally proportional to grain size. This lithofacies occurs in sets or cosets with sharp boundaries between individual sets and cosets are characterized by thin siltstone or mudstone layers, (Fig.4).

This lithofacies occurs when mega-ripples migrate. The tabular sets are probably formed by the migration of straight-crested forms, whereas the trough cross-bedding is formed by the migration of linguoid or lunate forms (Allen, 1963). The migrating mega-ripples coincide with the upper part of the lower regime of flow (Simon *et al.*, 1965). Trough cross-bedded sandstone is interpreted as the product of 3-D dune migration in channels under the conditions of the upper part of the lower regime or in filling of scour hollows (Collinson and Thampson, 1989). Trough cross-bedded sandstone is interpreted as the product of 3-D dune migration in channels under the conditions of the upper part of the lower regime or in filling of scour hollows (Collinson and Thampson, 1989).

Fig.4: Trough cross-bedded sandstone lithfacies at Zakho logged succession

- **Planar cross-bedded sandstone lithofacies**

Planar cross-bedded sandstone lithofacies (Fig.5) is composed of fine- to coarse-grained sandstone. The external geometry of this lithofacies is lenticular or irregular (wedge shaped). Planar cross-beds may be present as solitary sets or as cosets. Thickness of cosets ranges from 15 cm to a few decimeters in thickness. The contacts of this lithofacies are gradational. It is formed by the migration of straight crested dunes or bars deposited in the lower flow regime. It represents deposition on bars and or fluvial channels.

Fig.5: Planar cross-bedded sandstone lithofacies (↑) indicates reactivation surface at Zawita logged succession

- **Cross-laminated sandstone lithofacies**

Cross-laminated sandstone lithfacies (Fig.6) is composed of fine- to medium-grained sandstone and moderately to well sorted. The grain size of the sediments of this lithofacies decreases upward with upwards thickening of intercalated siltstone layers.

This facies is interpreted as being the product of currents in the lower part of the lower regime where the flow is tranquil (Simon *et al*., 1965). The migration of linguoid or lunate small-scale ripples produces small-scale trough cross-laminations (Allen, 1963). The variation of shape of cross-lamination is controlled by the hydrodynamics of flow, the grain size of material and the amount of material contributed from suspended mater. The preservation of only the lee side of the ripples implies that the bedload transport was predominant and that the contribution from suspension was negligible.

- **Interlayerd siltstone/ sandstone lithofacies**

Interlayered siltstone/ sandstone lithofacies (Fig.7) is composed of irregular alternations of mudstone, siltstone and very fine sandstone beds. Thickness of this lithofacies ranges from 4 m to 6 m and its contact boundary with the overlying lithofacies is regular. Thickness of a single bed is about 3 – 10 cm.

This lithofacies represents fluctuating conditions of fallout of suspended sediments and tractional working of the coarser parts as bedload. It reflects conditions of fluctuating current strength and the possible variable supply. The mode of origin is most likely to be that of sand being transported in an environment where mud deposition is taking place (as on some parts of the shelf). The mud sedimentation is interrupted by occasional heavy storms, which result in the deposition of sand layers. Similar facies have also been described from mixed intertidal flats. The mud is deposited during a period of slack water and immediately before and after the slack water conditions when there is still a weak current flowing (Reineck and Singh, 1973). This lithofacies is therefore regarded as a prodelta deposit or river overbanks.

Fig.6: Cross-laminated sandstone lithofacies at Amadiya logged succession

Fig.7: Interlayerd silt/ sand lithofacies with mudstone bed about 3 cm thick at Amadiya logged succession

- **Mudrocks lithofacies**

Two subfacies are recognized in the Mudrocks lithofacies, namely, Reddish-brown mudstone subfacies and Pale grey marl subfacies. The latter is restricted to the lower part of the formation only.

— **Reddish-brown mudstone subfacies:** Mudstone subfacies comprises thick mudstone beds reaching about 20 m. This facies consists of layers of mudrock that generally lack sedimentary structures and normally present in the form of red friable rocks (Figs.8 and 9).

The lower contact is more often gradual, whereas the upper contact is an irregular erosional surface (scour surface). This facies contains sometimes lenses of massive siltstone and/ or fine sandstone having lower sharp boundary and gradational upper boundary. Thickness of these sandstone beds ranges from few centimeters to about 1 m. Reddish-brown mudstone subfacies extends laterally from few hundreds of meters to over a kilometre. This subfacies occasionally contains cream to pale brown calcareous nodules. Diameter of the nodules ranges from few millimeters to several centimetres.

The Reddish-brown mudstone subfacies suggests deposition from quiet water as the clay particles needs a longtime to settle. Silts and clays are born as suspended load during floods as the speed of river water is high and as the speed of the current drops it leads to the deposition of silt granules followed by clay particles. The presence of mudstone beds associated with siltstone beds is evidence of sudden fluctuation in the speed of the flowing water. The colour of the mudstone is attributed to hydrated forms of ferriferous oxides as goethite or limonite present in the sediment or as coating around the clay particles. In many cases, yellow-brown colors are the result of recent weathering and hydration-oxygenation of ferrous iron minerals such as pyrite or siderite, ferroan calcite or ferroan dolomite. Mudstone subfacies occupy a large part of rocks of Injana Formation in all logged successions as it is believed that this facies covers wide area on both river banks as floodplain deposit. The carbonate nodules are of pedogenic origin, i.e. indicating fossil soils (calcrete) of semi arid climate.

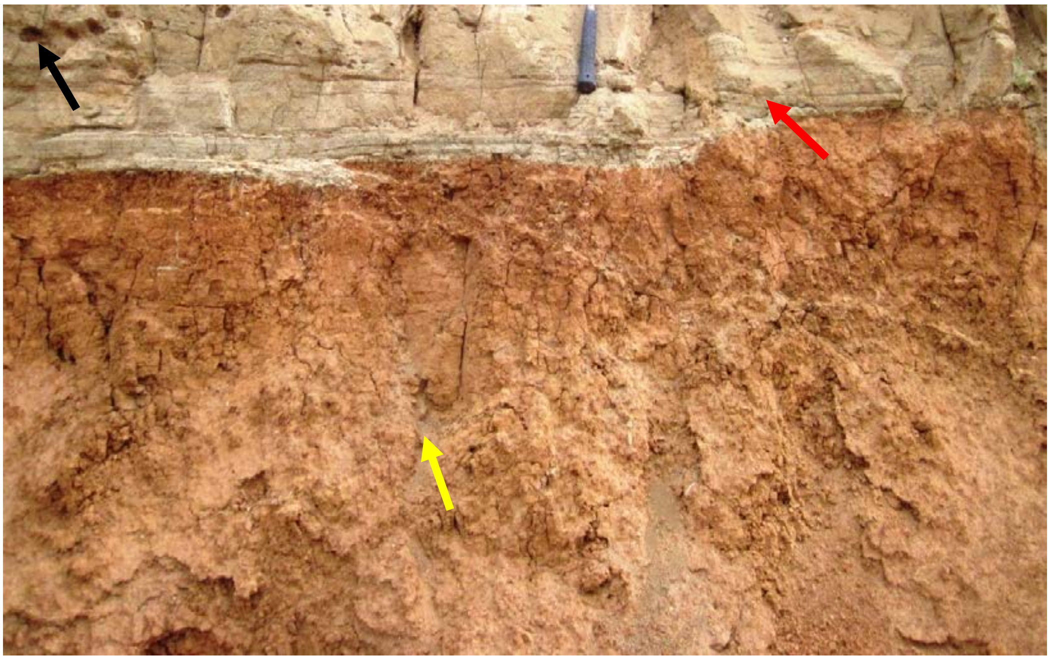

Fig.8: Mudstone subfacies, (↑) mud balls, (↑) calcareous and (↑) plane-bedded at Zakho logged succession

– **Pale grey marl subfacies:** This subfacies occurs almost only in the lower part of the formation. The pale grey marl subfacies is associated with the reddish brown mudstone subfacies (Fig.10). The lower contact of the former is commonly gradual whereas its upper contact is sharp. The top of the marl is frequently bioturbated. The bioturbation is represented mostly by vertical or inclined tubes to the bedding plane.

These general properties of the studied succession indicate that this subfacies is deposited in transitional environment with brackish water. The grey marls are more likely to be of marine influence whereas the red mudstones indicate subaerial exposure. The desiccation of the depositional site started earlier as shown by Mustafa (1980) during the deposition of the upper part of the Fatha Formation.

Fig.9: Flaser, lenticular and cross laminated, laminated lithofacies at Amadiya logged succession.

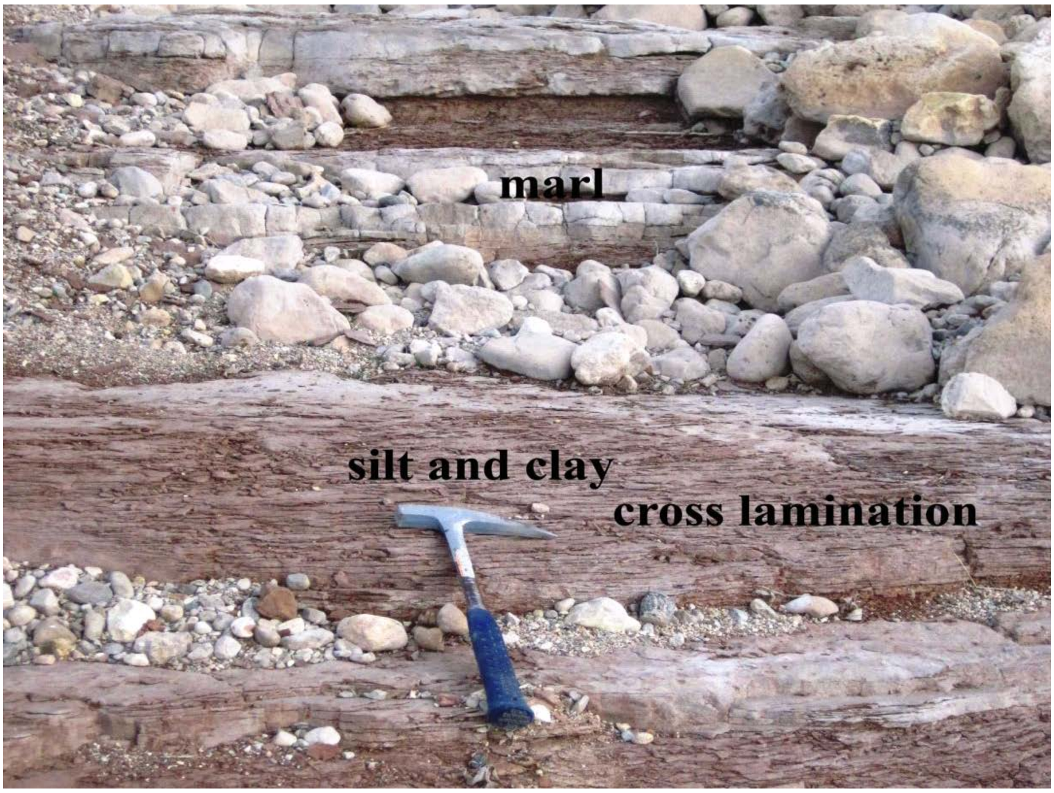

Fig.10: Marine deposits in the lower part of Injana Formation at Amadiya logged succession

Fig.11: Distributary channel at Amadiya logged succession showing several reactivation surfaces

FACIES ASSOCIATIONS

Eight facies associations are recognized in the logged successions. Two of them are limited to the lower part of the Injana Formation and immediately overlying the Fatha Formation and represent transitional environments. These facies associations are Mudflat and Deltaic. The rest are found in the upper part of the formation, representing fluvial environment and these facies associations are channel floor, point bar, chute and chute bars, abandoned channel, floodplain and crevasse splay. Each association will be described in such a way that it begins with the older (i.e. the transitional environment) then followed by the younger (i.e. fluvial environment) and the latter is the most dominant environment. It should be stressed here that the succession which is deposited in the transitional environment is relatively thin, ranging in thickness from 20 to 80 m. On the other hand, the succession which represents deposition in the fluvial environment ranges from 140 to 363 m. The columnar sections are constructed showing lithology, facies and interpretation of the logged successions on Figures 12, 13, 14 and 15.

- **Mudflats facies association**

It is found at the lower part of the Injana Formation in Zawita and Zakho logged successions. It comprises about 20 metres of Reddish-brown mudstone and Pale-grey marl subfacies with infrequent cross-lamination and flaser sandstone lithofacies. The marl has lower sharp and upper gradational contacts with the mudstone. This facies association represents deposition in mudflats with occasional influx of sands with current bedding. The grey marl reflects lagoonal influence.

- **Deltaic facies association**

It is found only at the base of the Amadiya logged succession. It is repeated four times as coarsening upwards successions (Fig.12) and overlies Fatha Formation. Each association ranges in thickness between 10 m and 35 m and consists (in ascending order) of mudrocks lithofacies, interlayer silt/ sand and mudstone, plane-bedded and cross-laminated sandstone and culminated with planar and/ or trough cross-bedded sandstone lithofacies. Interlayer silt/

sand lithofacies which is greyish reddish brown with flaser and cross laminations. The colour of these facies is generally reddish brown with grayish tint. The succession is, therefore, coarsening upwards. This facies association represents deltaic deposition with prodelta, distal bar, distributary mouth bar and distributary channel (Fig.12) subenvironments.

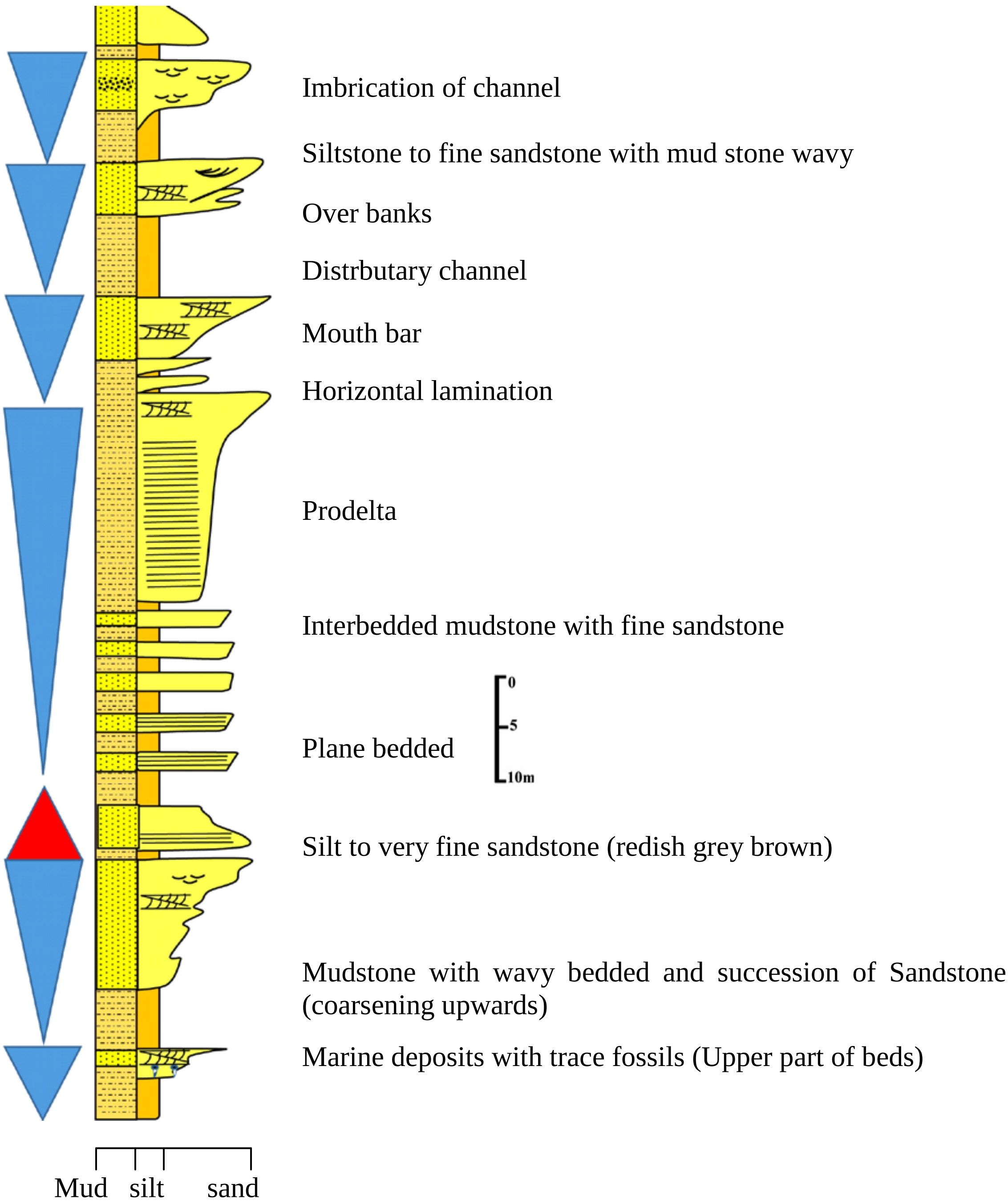

Fig.12: Coarsening upwards of sandstone in the lower part of Amadiya section (Deltaic environment) as in Stow (2012)

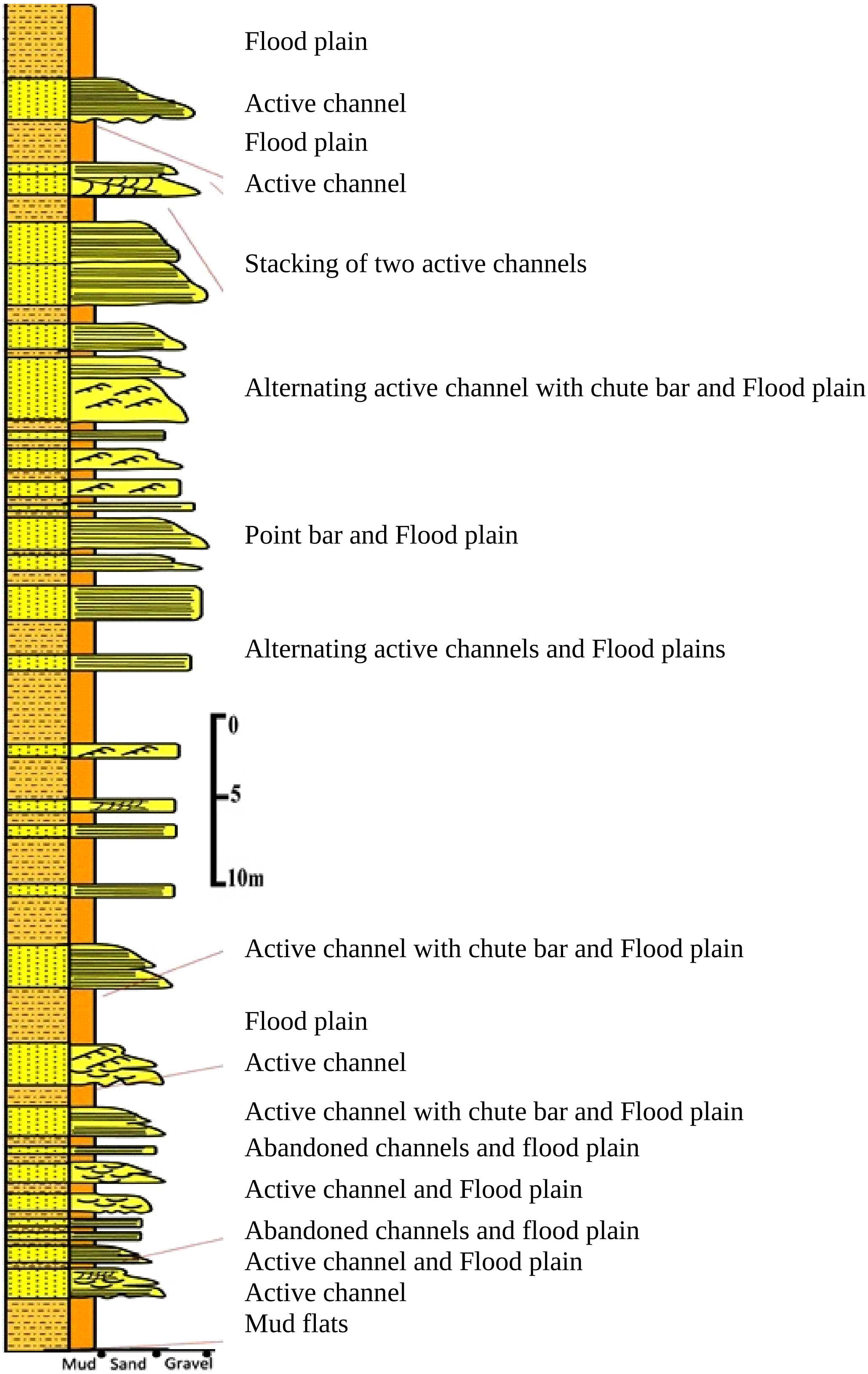

Fig.13: Fining upwards of sandstone in Zawita (meandering river)

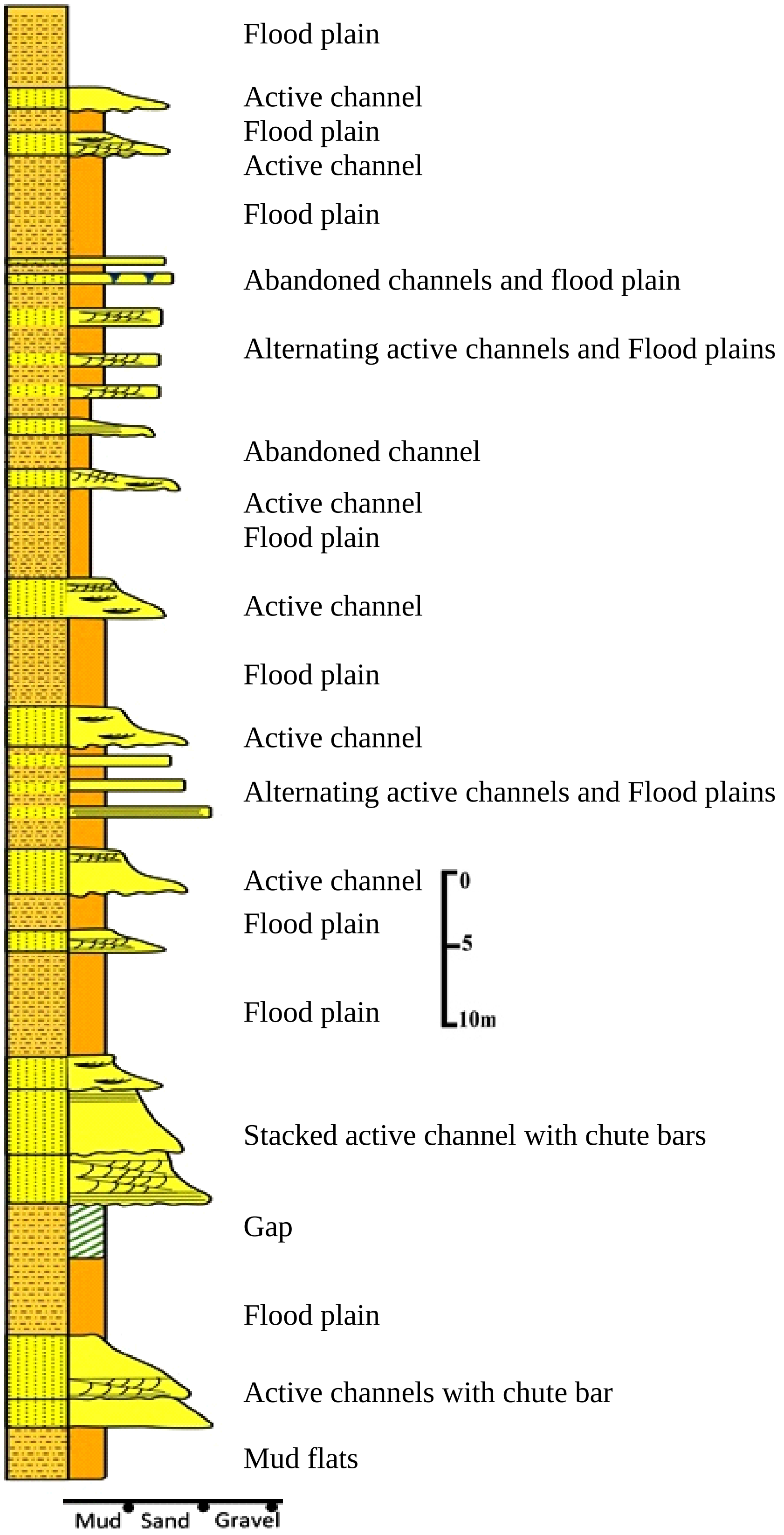

Fig.14: Fining upwards of sandstone in Zakho section (meandering river)

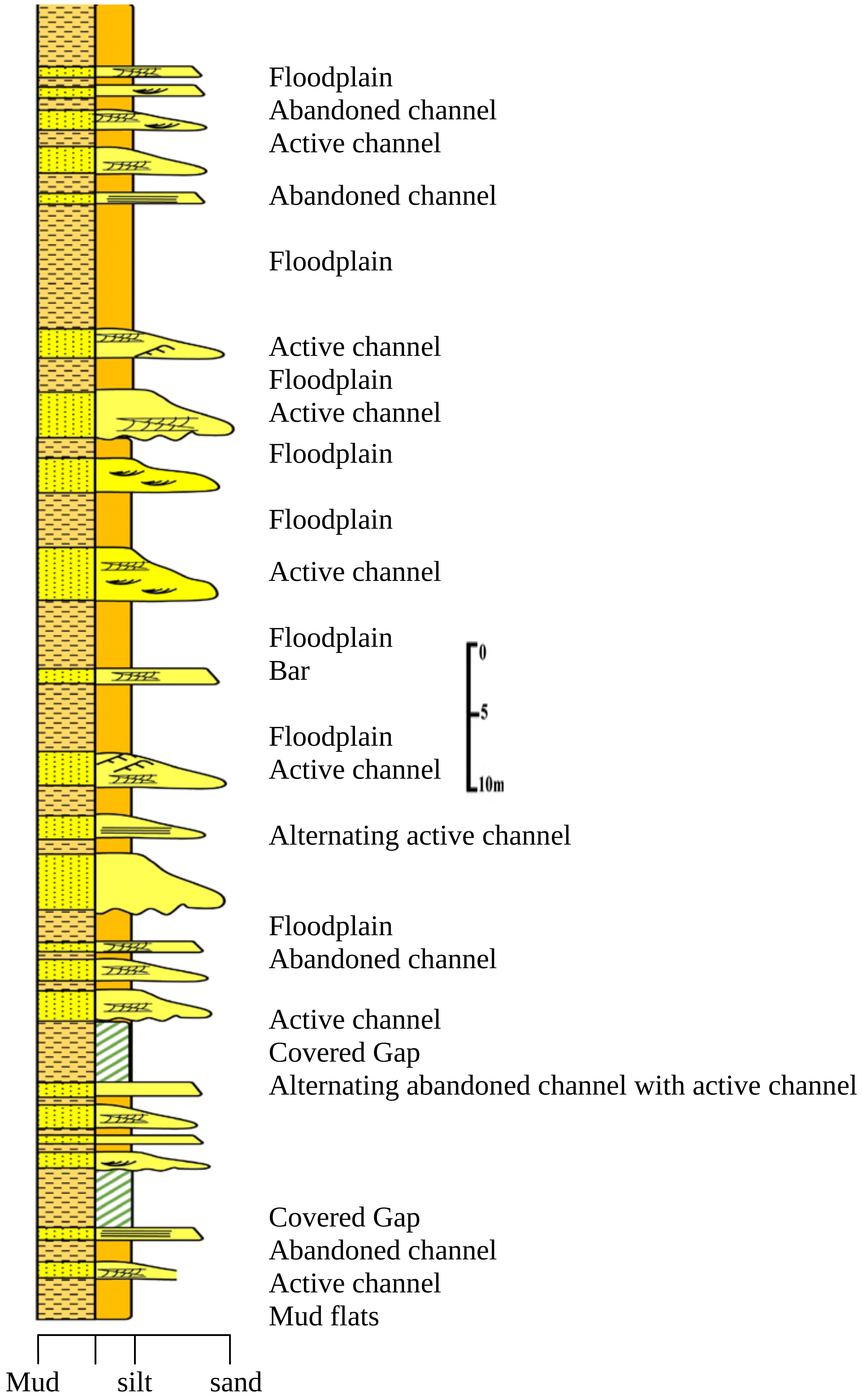

Fig.15: Fining upwards of sandstone in Amadiya section (meandering river environment)

- **Channel floor facies association**

Thickness of this facies association ranges between four to seven metres. It consists of several facies namely channel lag, plane-bedded sandstone, trough cross-bedded sandstone and planar cross-bedded sandstone (Fig.16a). The channel lag facies in its lower part of the association and its thickness ranges from 10 to 30 cm. Its lower contact is irregular with scour surface. Plane-bedded sandstone facies extends laterally for several to tens of metres. The trough cross-bedded sandstone facies extends similarly to several tens of metres and is usually close to the bottom of the succession. This association fines upwards and the boundaries between the facies are gradual. These facies represent the effective area of sedimentation channel which in some cases represent lateral, transverse and longitudinal bars too. Channel floor facies association indicates that the depositional environment is meandering river (i.e. high sinuosity stream) which contains many twists (Fig.15).

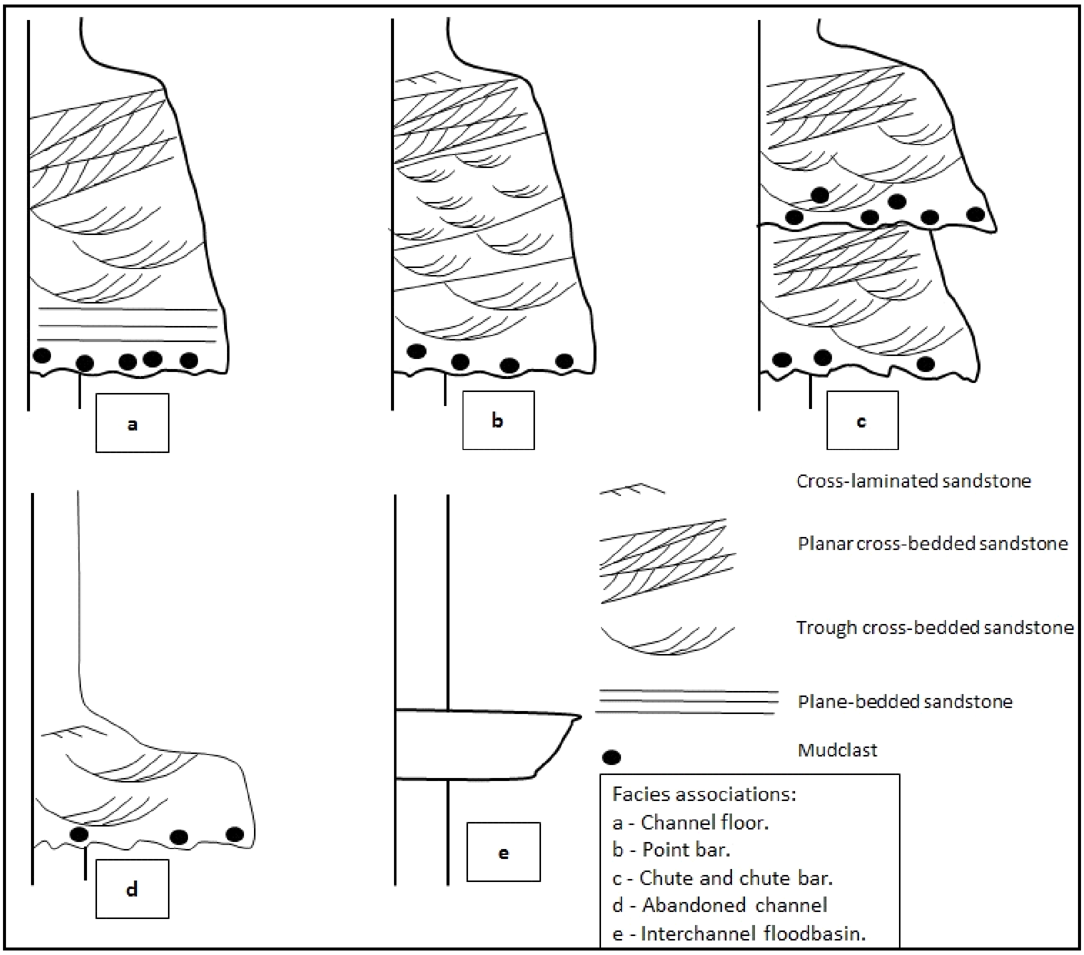

Fig.16: Five facies associations in the upper part of the Injana Formation in the Zawita, Amadiya and Zakho logged succession

- **Point bar facies association**

It is about two to six metres thick and consists of several facies, which fines upwards, namely channel lag, plane-bedded sandstone and/ or trough cross-bedded sandstone, epsilon cross-bedded sandstone and planar cross-bedded sandstone (Fig.16b). This facies association is characterized by the epsilon cross bedding of Allen (1970), which is heterogeneous and gently sloping. The planar cross-bedded sandstone lithofacies usually occupies the top part of point bar deposits. The channel lag lithofacies is found as lenses at the lower part of the association. Planar cross-bedded sandstone lithofacies is composed of fine sandstone deposited as a flood. The boundaries between the lithofacies are gradual and this association represents fining upwards succession. These deposits represent emergence of river bank due to the lowering of water level after flooding. This indicates different river energy from one area to another and for a short distance. Such association is located in point bar of a meandering river (Stewart, 1980).

- **Chute and chute bars facies association**

It is less common in the logged successions and is recorded from the lower part of Zawita logged succession and different parts of Zakho and Amadiya logged successions. Its thickness is about five metres. It occurs as sudden interruption to the fining-upwards succession by another new finining-upwards succession. The Chute and chute bar facies association comprises scour surface followed by coarse materials and occasional mudclasts, planar (and avalanche) cross-bedded and trough cross-bedded sandstones (Fig.16c). Such facies association is formed during flood stage as the river truncates across a point bar and deposits coarse bed-load sediments (Galloway and Hobday, 1983). The chute comprises the coarse materials including mudclasts and trough cross-bedded sandstone whereas the chute bar is characterized by the deposition of the planar and avalanche cross-bedded sandstone.

- **Abandoned channel facies association**

It is infrequent, about four to five metres thick. It starts with a scour surface followed by plane-bedded and/ or trough cross-bedded sandstone and culminate with mud plug (Fig.16d). The mud plug consists of a mixture of fine sediments, finer than the channel-fill deposits. The mud plug is about 2.5 metres thick.

- **Crevasse splayfacies association**

It is part of the channel margin facies and consists of massive (i.e. featureless) siltstone and very fine to fine sandstone. It exhibits coarsening upwards with upper and lower sharp contacts (Fig.16e). It ranges in thickness between 0.2 to 0.6 metres and it is not uncommon in the logged outcrops; found always within the mudstone lithofacies. They represent breach in the river bank during floods and partial buildup of sediments, mostly of the suspended load.

- **Interchannel floodbasin facies association**

It is also referred to as floodplain facies association. It comprises one major lithofacies, namely mudstone lithofacies. Its thickness ranges from 0.2 to about 20 metres. This facies has lower gradual contact with cross-laminated or cross-bedded sandstones. The upper contact is sharp and irregular marking the new fining-upwards succession. This facies association represents the fine suspended-load sediments that reach the interchannel area during floods i.e. floodplain deposits. They represent low sedimentation rates unlike the channel-fill deposits, allowing reworking by biota and plant growth. Pedogenic processes are revealed by the presence of carbonate nodules (calcrete) and plant rootlets. Calcrete indicates semi-arid and arid climate.

ARCHITECTURAL ELEMENTS

The concept of architectural elements is applied to the upper part of Injana Formation which represents the fluvial deposition. The lower part is partly covered as it is mostly soft mudstone whereas the concept of architectural elements requires good 3D exposures.

The application of concepts on fluvial architecture and sandstone bedforms has clearly improved the knowledge of fluvial succession (Lopez – Gomez *et al.*, 2009). It has been gradually recognized in the past decades that a river can produce a wide variety of facies succession, and similar successions can be formed in rivers of different style (Bridge, 1985; Miall, 1996). Architectural analysis pays particular attention to large scale sedimentary structures that are believed to reflect the type and behavior of bars and channels (Allen, 1986). The reorganization of large morphological features of rivers such as bars and channels by architectural analysis is crucial for the interpretation of ancient classification (Miall, 1985 and 1996). Five architectural elements are distinguished in Injana Formation deposits.

- **Downstream accretion elements**

It is introduced by Orton and Reading (1993) for foesetmacroforms (FM) a term introduced by Miall (1985). This element is composed of medium- to coarse-grained sandstone arranged into planar cross-bedded and trough cross-bedded. This element is lenticular in shape. Downstream accretion element forms the lower parts of the fining-upwards succession and generally shows a convex up shape either for the entire element or for individual succession within a single element as described by Miall (1985). This element is observed dominantly in the middle of the Injana Formation. Downstream accretion is probably formed by migration of linguoid or transverse bars (Collinson, 1996).

- **Lateral accretion element**

It is composed of fine- to medium-grained sandstone, heterogenous, low-angle inclined compound cosets of planar cross-bedding. This element is characterized by 2 to 6 m thick and 30 to 50 meters wide successions, dominantly in space fining-upwards pattern. This element is interpreted as components of point bars (Allen, 1964, 1970 and Olsen, 1988) and observed in all parts of Injana Formation, though infrequently.

- **Floodplain fines element**

It is characterized by red mudstone with interbeds of fine grained sandstone. Thickness of this element ranges from 0.2 to 20 m. The general geometry of this element is a sheet like shape, found in the upper parts of each fining-upwards succession of Injana Formation. Fine grain size of the floodplain fines element indicates deposition in the wide areas in juxtaposition to the main channel. Floodplain fines element is observed in all parts of Injana Formation.

- **Crevasse splay element**

Crevasse splay deposits consist of tabular- to wedge-shaped beds of massive sandstone with occasional thin ripple cross-laminations. Individual beds coarsen upwards, with sharp and non-scour surface. Thickness of the element ranges two to six decimetres. Crevasse splay element is invariably associated with Floodplain fines element. These elements are observed in all parts of the Injana Formation. Differentiating crevasse splay from levee deposits is often difficult because of facies similarities and lateral transitions between the two. Levee deposits are generally coarse grained, thick bedded and commonly display an overall wedge shaped geometry that tapers and thins away from the adjacent channel elements (Kraus and Wells, 1999). However, these elements are rarely preserved in the ancient deposits, especially in meandering rivers because during the construction of point bars on the inner side of the channel, it is accompanied by the erosion of the outer side, which comprises the levee deposit.

- **Abandoned channel deposits element**

Abandoned channel element consists of lenses of interlaminated mudstone, siltstone and fine-grained sandstone that immediately overlie fluvial channel element. These fines are usually referred to as mud plug and its thickness reflects the actual depth of the channel. (Galloway and Hobday, 1983). These channels commonly remain as lakes or ponds for a considerable length of time (Miall, 1996). This element is observed mainly in the lower part of Injana Formation as in Ashawa outcrop.

Paleocurrent analysis reveals that all logged successions show large changes in the current direction, which is characteristic of meandering streams Fig.17a and b. However, at the Zawita logged successions the meanders are more frequent and the kinks are sharper.

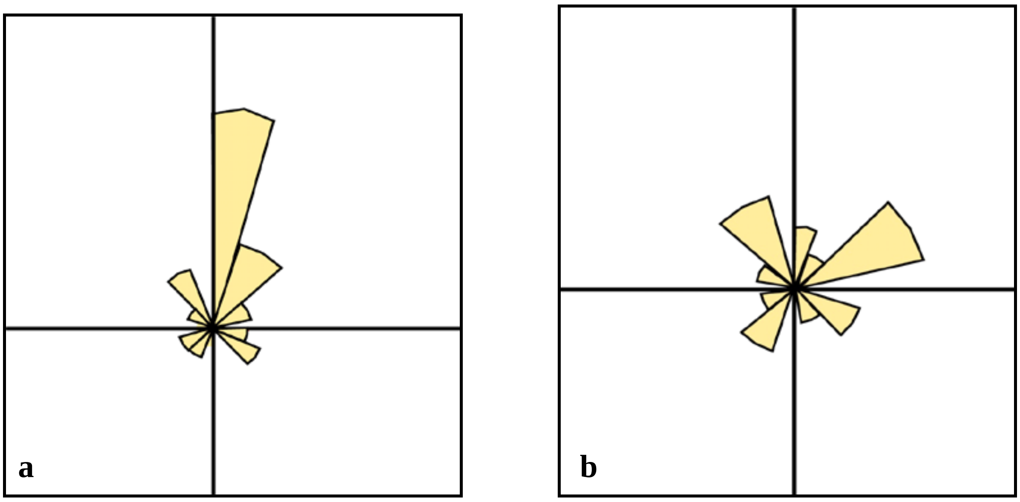

Fig.17: **a)** Rose diagram of paleocurrent analysis at Amadiya section, **b)** Rose diagram of paleocurrent analysis at Zawita section

DEPOSITIONAL ENVIRONMENTS

Two depositional environments are interpreted in the logged successions namely transitional and fluvial environment. Transitional environment is found at the lower part of formation with thickness about 80 metres at the lower part of Amadiya logged succession, 80 m at the lower part of Zakho logged succession and 20 m at the lower part of Zawita logged succession. It forms a minor part of the succession in all logged successions and by no means represents the dominant environment. The transitional environment at Amadiya logged succession is coarsening-upwards succession which represents deltaic environment. The deltaic deposits here consists of four facies representing prodelta, distal mouth bar, distrbutary mouth bar and distributary channel subenvironments. The transitional environment at Zakho and Zawita is dominantly mudrock facies which is soft and thus mostly covered.

The fluvial environment is deduced from the nature of nesting of facies, in a fining-upwards succession, the facies associations and the architectural elements. Six facies association are recognized. Channel floor, Point bar, Chute and chute bars, Abandoned channel, Crevasse splay and Interchannel floodbasin. These facies associations represent meandering river environment (i.e. high-sinuosity streams). The studied fluvial deposits of Injana Formation consists of five architectural elements namely, Downstream accretion, Lateral accretion, Floodplain fines, Crevasse splay and Abandoned channel. These elements characterize bar-dominated meandering river environment.

In comparison with the available depositional model, the classical fine-grained point bar sequence (Allen, 1964 and 1970; Galloway and Hobday, 1983 and many others) seems the most suitable model to explain the studied facies, their geometry and their vertical and lateral relationships. However, the chute-modified point bar model is applicable less frequently but it is present in the three logged successions.

In the field, the channel-fill deposits form belts of erosionally based meander belt sand lenses embedded in floodplain deposits. The upper boundary of the channel-fill deposits grades into the overlying fines. Multistory and vertically amalgamated channeled sandstone are common, especially near the top. Width to thickness ratio of meander-belt sand bodies are moderate and the sandstone are mostly medium to very fine grained. According to Schumm's classification of alluvial channels the majority are mixed-load channels because their width to depth ratio falls between 10 and 40, bedload (i.e. percentage of the total load) ranges between 3 and 11, and channel fill (i.e. percentage of silt and clay fraction) range between 5 and 20.

CONCLUSIONS

Seven lithofacies are recognized in the logged succession of Injana Formation, which combine to form eight facies association and five architectural elements. They indicate that the lower part of the formation, near the contact with the Fatha Formation, is deposited in transitional environments namely mudflats at Zawita and Zakho logged successions and deltaic at Amadiya logged succession. The major part (the upper part) of the Injana Formation represents deposition in meandering rivers (high sinuosity streams) with mixed-load channels. The paleocurrent direction changed from time to time.

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