Tectono sedimentary evolution of the Umm Ghaddah Formation (late Ediacaran-early Cambrian) in Jordan

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Abstract

The terrestrial Umm Ghaddah Formation of late Ediacaran-early Cambrian age was deposited in NE–SW elongated intracontinental rift system basins and sub-basins bounded by active listric half-graben faults. Basin fill consists of conglomerate facies association A, deposited in a fault-controlled transverse alluvial fan system that drained northwesternly and graded laterally into sandstone facies association B, deposited by a braided river system flowing northeasternly axial to the rift basin. The alluvial fan facies association was deposited by rock falls and non-cohesive debris flows of sediment gravity flow origin, and by sheetflood processes.

The Umm Ghaddah Formation is dominated by a large-scale fining upward succession interpreted to reflect a gradual cessation of the Pan African Orogeny. Within this large-scale trend there are also minor fining and coarsening upward cycles that are attributed to repeated minor tectonic pulses and autocyclic shifting of the system.

The distribution pattern of the Umm Ghaddah Formation and the underlying Ediacaran Sarmuj Conglomerates, Hiyala Volcaniclastics and Aheimir Volcanics in Jordan and adjacent countries in isolated extensional half-grabens and grabens formed during the extensional collapse phase of Arabia associated with the Najd Fault System seems to be unrelated to the present day Wadi Araba-Dead Sea transform fault system.

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1. Introduction

The clastic Umm Ghaddah Formation has been recently documented by Amireh and Abed (2000), and interpreted as an intracontinental rift basin-infill sequence, or a syn-rift fill. It is exposed at three localities in central Jordan and has been identified in a series of wells (Fig. 1). The formation consists dominantly of conglomerate (Fig. 2a) and minor sandstone facies. It overlies unconformably either the Aheimir Volcanic Suite (Table 1 and Fig. 2b) of 553 ± 11 Ma (Jarrar, 1992) or directly the Sarmuj Conglomerate (Table 1 and Fig. 2c) of 595–600 Ma (Jarrar et al., 1991) and is conformably overlain by the Saleb Arkosic Sandstone Formation (Table 1 and Fig. 2d) of early Cambrian age (Bender, 1968; Amireh et al., 1994).

Since the Umm Ghaddah Formation is stratigraphically confined between the Aheimir Volcanics or the Sarmuj Conglomerate of Ediacaran age and the Saleb Arkosic sandstone that is dated by Amireh et al. (1994) to be of early Cambrian age according to presence of Cruziana aegyptica ichnofossil, the Umm Ghaddah Formation can be constrained to a late Ediacaran-early Cambrian age following the International Stratigraphic Chart of 2004 (Gradstein et al., 2004).

The unconformity surface between the Neoproterozoic basement complex and the Cambrian sediments could be either an erosional peneplain surface (Fig. 2c) or a pronounced paleorelief (Fig. 2b) resulting from graben and horst structures produced by rifting through the extensional phase of the Pan African Orogeny that affected...
Jordan and the entire north African and Middle East region (Stern et al., 1984; Bentor, 1985; Husseini, 1989, 2000; Jarrar et al., 1991, 1992). This unconformity surface seems to be not relevant to the late Neoproterozoic glaciation events that gave rise to the “Snowball Earth” and affected regions located even at low latitudes, as will be discussed below.

The tectono-sedimentary evolution of the late Ediacaran-early Cambrian Umm Ghaddah Formation is explained here, in the context of an extensional half-graben model. Amireh and Abed (2000) gave no detailed facies analysis of the Umm Ghaddah Formation, nor did they decipher the type, geometry and orientation of the invoked rift basins.

The present work analyses the facies of the Umm Ghaddah Formation in order to determine the depositional environment, and to compare the formation with possible modern analogues. It also aims at revealing the
configuration and regional and tectonic evolution of the Ediacaran rift basins. Is this late Precambrian rift related to the present day Dead Sea transform fault as proposed by many authors (Bender, 1968, 1974, 1982; Weissbrod and Karcz, 1988) or not is a question attempted to be answered by the present paper.

2. Methods and terminology

The Umm Ghaddah Formation has been studied in seven sections cropping out at the following three localities: Wadi Umm Ghaddah (the type locality at 30°26.0′N and 35°22.36′E), Wadi Abu Khusheiba (30°16.347′N and 35°18.375′E) and Wadi el Mahraka (31°06.446′N and 35°31.689′E) (Fig. 1). According to the limited number of outcrops, six wells have also been investigated, which are: Ajlun-1 well (AJ-1), Hammar-2 well (HM-2), Northern Highlands-1 well (NH-1), Wadi Sirhan-3 well (WS-3), Wadi Ghadaf-2 well (WG-2) and Fuluq-1 well (F-1) (Fig. 1).

The term facies is used to convey grain size, textural parameters including type of framework support, orientation fabric, grading, roundness, sorting and type of stratification, as well as sometimes the internal structures and geometry of clastic bodies.

Scaled field photographs were used to determine the sorting, roundness and sphericity by visual estimation using Powers’s (1953) chart, and percent of matrix.

Grain size analysis (based on one phi interval) was conducted on the finer than coarse pebble fraction that constitutes the matrix between the framework clasts. The weight of sieved samples ranges from 1 to 1.5 kg. Atterberg cylinders were used to determine the clay fraction of these samples. The grain size scale of Blair and McPherson (1999) modified from Udden-Wentworth scale is used, since it is useful for the coarse gravels of alluvial fans.

3. Geologic setting and stratigraphy

The Precambrian-Cambrian boundary has been recently determined according to the appearance of the trace fossil *Phycodes pedum* which is preserved as a series of branched, hypichnial ridges on the lower surface of a sandstone bed (Brasier et al., 1994). Such trace fossil is not identified neither in the sandstones of the Umm
Ghaddah Formation (facies B) nor in the conformably overlying Saleb Arkosic Sandstone Formation. On the other hand, the reliable marker trace fossil identified indicative of the early Cambrian is *C. aegyptica* in the Saleb Arkosic Sandstone, located 100 m above the basement complex (Amireh et al., 1994). Thus it is very difficult to determine the exact Precambrian–Cambrian boundary, is it at the contact between the two formations, or more probably somewhere below this contact. Therefore, as stated above, the Umm Ghaddah Formation is considered of late Ediacaran-early Cambrian age.

This stratigraphic position of the Umm Ghaddah Formation is portrayed in Table 1. The underlying Neoproterozoic crystalline basement, Aqaba Complex, consists mainly of granitoids and sporadic occurrences of mafic and ultramafic rocks that range in age from 800 to 610 Ma (Lenz et al., 1972; Bender, 1974; Jarrar, 1985; Rashdan, 1988; Jarrar et al., 1993), and locally of younger (Ediacaran) alkaline rhyolite lava flows (Aheimir Volcanic Suite, McCourt, 1988) and equivalent Feinan Granites (Jarrar et al., 1991). At specific localities, anchimetamorphic Sarmuj Conglomerate sequence and a slate-pyroclastic succession of the Hiyala Volcaniclastic Formation make up the uppermost part of the Precambrian basement (McCourt, 1988; Jarrar et al., 1991). These igneous and metamorphic rocks constitute the northernmost flank of the Arabian–Nubian Shield.

The oldest rocks in the basement complex of Jordan are high-to medium grade gneisses and metasediments (Jarrar, 1985), which were intruded during the Pan African Orogeny by voluminous calc-alkaline granitoids (Jarrar, 1985). The evolution of the Pan African Orogeny was terminated by bimodal magmatic activity and post-orogenic deposition of a rift-related magmato-sedimentary
intermontane succession (Jarrar et al., 1991). The Precambrian was terminated by an isostatic uplift of the juvenile crust. The uplift gave rise to an unconformity in form of a profound erosional surface (peneplain), or a much less significant irregular relief separating the Neoproterozoic basement from the Cambrian sandstone (Bender, 1968; Abed, 1985; Ibrahim and Rashdan, 1988).

Although it is expected that a glaciation event could have occurred in the study area at the final uplifting stages of the Pan African Orogeny that caused relief elevation which in turn may have triggered the Marinoan ice sheet as well as local mountain glaciers (Deynoux et al., 2006), no sort of any evidence of glaciation has been found neither in the Umm Ghaddah Formation nor in the underlying or overlying sequences.

Therefore, this unconformity separating the Neoproterozoic basement from the Cambrian sedimentary sequence was probably not related to the erosional phase accompanying the Neoproterozoic Marinoan/Varanger glaciation event. This glacial event, the so-called “Snowball Earth” event, that extended to low latitudes (down to 15–24°S) and terminated at 635 Ma (Allen, 2006), or any younger glaciation event like the Squantum-Gaskiers (dated 582 Ma) did not affect the study area during the Ediacaran to early Cambrian because:

1. No evidence of any sort of glacially related deposits, such as glacial diamictites, striated substrates, striated, faceted and shaped clasts, lacustrine varves with dropstones, post-glacial glacioeustatic transgressive sequence, or cap carbonates has been reported neither in the rocks under discussion, that is Umm Ghaddah Formation, nor in the underlying Sramuj Conglomerate–Hiyala Volcaniclastics, or in the overlying Saleb Arkosic Sandstone.

2. All these Precambrian glacial events are much older than the invoked unconformity separating the latest Neoproterozoic basement from the early Cambrian deposits.

3. The paleoposition of the Arabia was at low latitude (about 15°S south) as can be seen in Fig. 10 which probably did not allow sea level glaciation at the time of deposition of the Umm Ghaddah Formation. Although, as mentioned above, the older Marinoan/Varanger Neoproterozoic glaciation event affected low latitude regions (15–24°S), the fact of having no single glacial evidence pertaining to Umm Ghaddah Formation, could lead to the conclusion that such low latitudes were not influenced by other younger glaciation events, if they exist, at the close up of the Neoproterozoic Era.

From other point of view, Fig. 10 also shows the successive positions of Arabia from 600 Ma till the Devonian. In the late Ordovician, the study area, as part of northwest Arabia was located at about 55°S (Konert et al., 2001), where glaciation affected NW Arabia. The first and third authors of the present paper were the first to record this late Ordovician glaciation event in southern Jordan (Abed et al., 1993).

The subsequent Phanerozoic sedimentation took place on the stable shelf of Gondwana that flanked the southern (Baltic) margin of the Paleo-Tethys Ocean (Amireh et al., 1994). Sedimentation began with continental conditions, where braided rivers dominated through the Cambrian draining the Arabian–Nubian Shield and gave rise to the Saleb Arkosic Sandstone and Umm Ishrin Sandstone Formations (Table 1). Jordan and the entire Middle East region were influenced by a major transgression of the Paleo-Tethys seaway in the late-Early to early-Middle Cambrian (Amireh et al., 1994) that was responsible for deposition of the regional Burj Limestone Formation (Table 1).

The Ordovician Period, similarly started by continental braided river sedimentation, but was gradually replaced by marine conditions, that covered Jordan and the adjoining countries and persisted throughout the late Ordovician and the subsequent Silurian Period (Bender, 1968; Khalil, 1994; Droste, 1997; Amireh et al., 2001). No late Paleozoic deposits have been found in Jordan, which were probably deposited but later truncated by the “Hercynian” unconformity (Andrews, 1991; Konert et al., 2001).

4. Facies description and interpretation

The Umm Ghaddah Formation outcrops have been studied at the three localities mentioned above (Fig. 1). Due to the inaccessibility to the Wadi Umm Ghaddah and Wadi el Mahraka areas, only one exposure of the Umm Ghaddah Formation has been studied in each locality (Fig. 3). Five outcrop sections have been measured in Wadi Abu Khusheiba (Fig. 4). The type locality of the Umm Ghaddah Formation is considered to be at Wadi Umm Ghaddah (Amireh and Abed, 2000), where it attains a maximum thickness of 60 m (Fig. 3). This outcrop forms a NE-extending belt that is located between the exposed Aheimir rhyolites and the Upper Cretaceous and Tertiary carbonates.

The analysis of lithofacies and architecture of the Umm Ghaddah Formation at the outcrops has revealed alluvial fan and braided river facies associations. The former constitutes the entire Umm Ghaddah Formation at Wadi Umm Ghaddah and Wadi Abu Khusheiba, whereas the braided river facies association is restricted to the Wadi el Mahraka (Fig. 5).

4.1. Facies association A: alluvial fan

Facies association A consists of four facies made up mainly of reddish brown clast-supported conglomerate. These conglomerates are composed almost entirely of rhyolitic rock fragments with granule to sandy matrix of the same composition, thus can be called rhyolite petromict conglomerate. The facies association displays the principal characteristics of an alluvial fan deposit as defined by Bull (1972), Blair and McPherson (1994), Blair (1999a,b,c) and Went (2005).

This alluvial fan depositional environment is interpreted according to a thick sequence of a conglomerate having
Fig. 3. Log of the Umm Ghaddah Formation in Wadi Umm Ghaddah (type locality) illustrating the variations in grain size, sedimentary structures and facies distribution, position of samples (UG1–4) and facies interpretation. Lower arrow indicates direction of pebble imbrication, whereas central and upper arrows indicate orientation of channel axis.
clasts ranging in size from pebbles up to fine blocks, absence of horizontal bedding, absence of body or trace fossils, very poor sorting, the occurrence close to the Aheimir volcanic source rocks, the red color indicating the general oxidizing conditions prevailing in alluvial fans, and scarcity of sedimentary structures (Bull, 1972; Nilsen, 1985). In the fan site, adjacent to the Aheimir volcanic source rocks, the dominant depositional processes appear to have been sediment gravity flow processes including rock fall, unconfined debris flows and sheetfloods. A contemporaneous braided river system developed away from the fan site, at the center of a half-graben basin, forming facies association B. Within facies association A, there is a change in facies corresponding to down-fan transition from proximal to distal fan.

Facies A1 and A2 represent proximal alluvial fan facies, deposited by sediment-gravity flow processes including mainly non-cohesive debris-flows (sub-aerial, high viscosity debris flow of Gloppen and Steel, 1981) of facies A2 and less common rock falls of facies A1. On the other hand, fluid gravity processes (stream flow) gave rise to mid to distal alluvial fan sheetflood deposits of facies A3 and incised-channel flood deposits of facies A4.

Pebbles, cobbles, boulders and blocks were generated in upland drainage areas by collapse of bedrock cliffs and colluvial slope failure in response to fracturing and weathering under the influence of gravity (Hadley, 1964; Harp and Keefer, 1989). These destabilized materials were then transported downward from the drainage basin towards the

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**Fig. 4.** Five logs of the Umm Ghaddah Formation in Wadi Abu Khusheiba (two logs in (A) and three logs in (B)) illustrating the variation in grain size, sedimentary structures and facies distribution, sample position (Abk1–4) and facies interpretation.
alluvial fan site mainly by sediment-gravity flow processes and partly by fluid gravity processes of catastrophic storms or intense thunderstorms (Middleton and Hampton, 1976; Blair and McPherson, 1994; Blair, 1999b). The absence of stratification, and any structure or fabric indicating fluid flow processes in facies A1 and A2 suggest that these facies were not deposited by fluid-gravity flows, but by sediment gravity flow processes. On the other hand, stratification and orientation of clasts suggest that water flow processes, particularly sheetflood flows were responsible on deposition of facies A3 and A4 (Nilsen, 1985).

4.1.1. Facies A1

This facies consists of massive, clast-supported (less than 10% sandy matrix), very poorly sorted, sandy, coarse cobble to fine block conglomerate (Fig. 6a and c). The clasts are randomly oriented, subrounded to rounded. This facies occurs in the lowermost 25 m interval of the Umm Ghaddah Formation in the type locality (Fig. 3) and the lowermost part at Wadi Abu Khusheiba (profile no. 1; Fig. 4A). It is intercalated with the other facies (Figs. 3 and 4A and B). No type of stratification or internal sedimentary structures is visible in this facies (Figs. 2a and 6a). Clasts are up to 5.5 m in size (Fig. 6c) and the mean size of the 10 maximum clasts within each unit varies from 70 to 150 cm (Figs. 3 and 4A and B). The clasts are invariably subrounded to rounded and vary in shape from discoidal to oblate.

Grain size analysis of the matrix [<1.6 cm (finer than −4φ) fraction in the interstices among clasts] reveals that it ranges from silt to medium pebbles (sample UG1, Table 2) and is poorly sorted (SI = 1.8). The granule, fine pebble and medium pebble fraction accounts for 42% (weight percent) of the matrix (sand 54% and silt 4%). No clay has been found in this fraction. Therefore, facies A1 has a sandy (slightly silty) matrix that makes up less than 10% of total rock volume.

The oversized boulders reaching up to 5.5 m in diameter that float in the surrounding cobble to boulder-sized conglomerate can be interpreted as a rock fall deposit (Gardner, 1983; Blair and McPherson, 1994, 1999; Blikra and Nemec, 1998; Nemec and Kazanci, 1999). They were, probably, generated from the graben scarp by bedrock cliff failure and moved downward by the influence of gravity, and tumbled directly at the base of the fault scarp or rolled over or bounced a little distance to the proximal fan (Beaty, 1989; Blair and McPherson, 1994; Nemec and Kazanci, 1999). The rock fall avalanches were related to bedrock weathering, as well as to heavy rainfall and thunderstorms (Nemec and Kazanci, 1999). Such rainfall was available under the hot-humid climate prevailing during the time of Umm Ghaddah Formation, as indicated from the position of the study area within Arabia at the late Neoproterozoic time 15° south of the equator (Fig. 10), as well as from the reddish brown color persisting throughout the formation (cf. Nemec and Kazanci, 1999).
The presence of a sandy, slightly silty matrix in this facies can be attributed to subsequent infilling of original interclast pores with sand and silt percolated downward (cf. Nemec and Kazanci, 1999).

The unusually well rounded clasts may indicate strong abrasion action due to clast-to-clast collision during a relatively long distance of transport through the fan catchment area to the fan site (Nilsen, 1985). An alternative explanation could be mechanical weathering, particularly exfoliation in the rhyolitic source rocks as compared to such processes prevailing at the present time in several localities in Jordan.
4.1.2. Facies A2

This facies is clast-supported with variable content of sandy matrix ranging from 10% to 25%. It is ungraded to inversely graded, and disorganized (Fig. 2a). Clasts are randomly oriented and rounded to well rounded, discoidal to oblate-shaped, very poorly sorted, sandy, pebbly, cobble to fine boulder-grade (Fig. 2a). This facies is the most abundant one in the type locality (Fig. 3), and three profiles of Wadi Abu Khusheiba (Fig. 4A and B). Similar to the previous facies, there are no internal sedimentary structures or external stratification in the beds, but it is characterized by having smaller-sized clasts and containing more sandy
matrix. A few channels have been found filled with slightly oriented clasts (facies A3) (Figs. 3 and 4). Mean grain size of 10 maximum clasts of units of this facies, varies from 7 to 30 cm (Figs. 3 and 4). The matrix consists of poorly sorted silt to medium pebbles (SI = 1.55–1.78) (samples UG1, UG3, ABK1 and ABK2, Table 2). The granule, fine and medium pebbles account for 44–58% (40–54% sand, 2% silt).

According to the coarse grain size (boulder to fine blocks), absence of stratification, rarity of sedimentary structures, random orientation of clasts and the rather poor sorting, facies A2 is attributed as a cohesionless debris flow deposit (Bull, 1972; Walker, 1975; Heward, 1978; Wells and Harvey, 1987; Blair, 1999c; Jarrett and Costa, 1986; Blair, 1987a; Blair and McPherson, 1994). Non-cohesive sediment-gravity flow is generated by high-water discharge down a steep channel containing abundant sediments (Church and Desloges, 1984).

This type of flow has been recorded in the recent Roaring River alluvial fan of the Rock National Park, Colorado Mountain (Blair, 1987a) and in the present alluvial fans of Howgill Fells, northwest England (Wells and Harvey, 1987).

Debris flows are generally related to a thick weathering cover or other metastable accumulation of debris, and tend to be triggered by heavy rainfall (Nemec and Kazanci, 1999). Moreover, these debris flows were common in the pre-vegetation times, such as the Precambrian (Eriksson et al., 1999; Went, 2005).

Both facies A1 and A2 of rock fall and non-cohesive sediment gravity flow processes were most likely deposited in the proximal part of the alluvial fan (Hooke, 1967; Bull, 1977; Gloppen and Steel, 1981; Nilsen, 1982). These processes are usually associated with each other as in many modern alluvial and colluvial fans (Nemec and Kazanci, 1999; Turner and Makhlof, 2002). On the other hand, the finer, stratified and oriented and better sorted facies A3 and A4 might represent mid to distal fan facies (Hooke, 1967; Bull, 1977; Gloppen and Steel, 1981; Nilsen, 1982).

4.1.3. Facies A3

Facies A3 consists of clast-supported conglomerate with a sandy matrix varying from 10% to 30%. Beds are ungraded, poorly sorted and consist of sandy, pebbly, fine to coarse cobble conglomerate (Fig. 7a). Clasts are parallel oriented, subrounded to rounded and discoidal to oblate. This facies occurs at 15 m above the base of the formation and in the upper 15 m in section Wadi Umm Ghaddah (Fig. 3), and constitutes a small proportion of profiles no. 1 and 2, and most of profiles no. 3, 4 and 5 in Wadi Abu Khusheiba (Fig. 4). It is crudely stratified (Fig. 7b). In Wadi Umm Ghaddah it shows clast imbrication, revealing a NNW dispersal direction (Figs. 3 and 6d and 7c). This facies has sharp but non-erosional lower boundaries. Mean size of 10 maximum clasts is 7 cm (Figs. 3 and 4).

The matrix ranges from silt to medium pebble-grade (samples UG2, UG4, ABK3 and ABK4, Table 2) and is poorly sorted (SI = 1.32–1.78). The granules, fine and medium pebbles account for 33–55% (44–65% sand, 1–25% silt).

The facies A3 was most likely formed by sheetfloods in the mid to distal alluvial fan. This interpretation is supported by the presence of stratified gravels and sands, the clasts parallel to bedding planes, the sheet-like geometry, the moderate sorting of clast-supported pebbles and cobbles, and absence of cross-bedding (Gloppen and Steel, 1981; Nilsen, 1985; Blair and McPherson, 1994; Nichols and Hirst, 1998; Blair, 1999a,b; Nemec and Kazanci, 1999; Went, 2005).

Sheetfloods are unconfined (unchannelized) water flows moving down a slope. When the non-cohesive sediment-gravity flow reached the mid to distal fan site, it became completely unconfined and laterally expanded outward forming a sheetflood (Blair, 1987a). Sheetfloods are surges of sediment-laden water spread out from the end of the stream channel on a fan (Bull, 1972), or supercritical standing waves of expanding sheetflood on the fan (Blair, 1999b). Such supercritical (upper flow regime) flow conditions resulted from high fan slope, and high sediment and water discharge (Blair, 1999b). Transportation of gravel in the sheetfloods occur generally as a bedload by tractive forces under supercritical flow conditions (Blair, 1987a), whereas imbrication may indicate, particularly, rolling (Blair, 1987a).

The lower percentage of fine pebbles and the more sand content of facies A3 than facies A2 may indicate that the facies A3 was more distal in the fan system than facies A2. Therefore, debris flow processes dominating the proximal fan were replaced by stream flow processes that dominate the distal fan (Smith, 1970; Wells and Harvey, 1987).

4.1.4. Facies A4

Facies A4 is a lenticular to channel-shaped conglomerate (Figs. 7d and 8a). It is clast-supported with 20–40% sandy matrix. Such high content of sandy matrix in clast-supported conglomerate is recorded by Blair (1987a). This facies is largely ungraded, internally stratified, moderately sorted and consists of sandy, granular to pebble-grade conglomerate. The clasts are subrounded to rounded and discoidal, oblate to prolate in shape. Three units of this facies are encountered within the lower, middle and upper parts of the formation in Wadi Umm Ghaddah (Fig. 3); one unit in the central part of profile no. 4, and another unit in the upper part of profile no. 2 in Wadi Abu Khusheiba (Fig. 4). The lenses or channel fills are either convex downward (Fig. 8a) or irregular, whereas their tops could be flat (Figs. 7d and 8a) or also irregular. Axes of these lenses or channels are dominantly NNW-ward.

There is a shale layer (Fm) (10–15 cm thick) in Sections 2, 4 and 5 in Wadi Abu Khusheiba (Fig. 4), interbedded within facies A2 and A3 (Fig. 7b). X-ray diffraction analysis of this shale shows that it consists of kaolinite and illite.
The lower 25 m of the formation in Wadi Umm Ghaddah is characterized by the large clasts of facies A1, whereas the upper 35 m exhibit a gradual decrease in clast size, showing an overall fining upward tendency (Fig. 3). On the other hand, in Wadi Abu Khusheiba, five outcrops are characterized by several coarsening and fining upward units (Fig. 4).

The granule- to pebble-conglomerate and pebbly coarse sandstone channel fills and lenticles with their faint internal stratification and faint lamination may be interpreted as incised channel fills that represent an extension of the drainage-basin feeder channel onto the fan (Blair and McPherson, 1994), or a cut-and-fill structure by channels entrenched only a short distance downslope from the fan apex (Bull, 1972). Another interpretation could be deposition in incised shallow channels in the sheetflood deposits of distal fan during waning flood discharge or recessional flood clear-water flows (Gloppen and Steel, 1981; Nilsen, 1985; Blair, 1987a; Blair and McPherson, 1994; Nichols and Hirst, 1998; Nemec and Kazanci, 1999). The channel fills would indicate NNW-ward runoff from the fan apex (Figs. 3 and 4).

The stratification characterizing this facies, visible due to segregation of pebble-rich, granule-rich and sand-rich horizons, similarly to facies A3, is attributed to upper flow regime deposition by a shallow supercritical flow (Blair, 1987a).

The thin shale unit (Fm) interbedded within facies A3 and A2 in Wadi Abu Khusheiba (Figs. 4 and 7b) might be interpreted as a mud deposit at the end of distal lobe, where mud was deposited in a small topographic depression where ponding occurred (Bull, 1972; Blair, 1987a). Or, it can be interpreted as having formed during a period when no deposition was occurring on the fan because of reduced supply, allowing the axial fluvial sediments to build up over the fan (Gloppen and Steel, 1981; Nichols and Hirst, 1998).

4.2. Facies association B: braided river

In Wadi el Mahraka, the Umm Ghaddah Formation unconformably overlies the Ediacaran Sarmuj Conglomerate (Fig. 2c) attaining a thickness of 30 m (Fig. 5). The formation consists of facies association B, but with four intercalations of beds of facies A2 that are located within its upper half (Fig. 8b). Facies association B shows three sandstone lithofacies: planar tabular cross-bedded (Sp; Fig. 8c), trough cross-bedded (St; Fig. 9), and horizontally...
laminated sandstone (Sh; Fig. 8c). Sp is the major lithofacies having unit thicknesses of 20–90 cm. The Sp and St are composed of pebbly, medium-grained, poorly sorted (Table 2) sandstone, whereas the Sh is made of fine-grained, well sorted sandstone.

Grain size analysis of the dominant lithofacies, Sp, reveals fine pebble to silt-grade (Table 2), with a mode at medium sand, and is poorly sorted ($SI = 1.71$). The fine pebbles and granules account for 11%, sand 87% and silt 2%. No clays have been detected. Microscopic analysis shows that the sand grains are subrounded to rounded, and of moderate to high sphericity.

The three lithofacies constitute sandstone sheets (downstream accretion macroforms, DA, of Miall, 1996) of 1–5 m thickness that extend laterally across the entire width of the outcrop (Fig. 8b). These sandstone sheets usually start with a planar to slightly irregular base that might truncate the underlying sheet. Some of these sheets have a basal gravel lag and may exhibit a fining upward tendency.

The paleocurrent direction based on three-dimensional planar foreset azimuths and axes of the trough foresets is NEE and NE, respectively (Fig. 5). Therefore, the dispersal direction of the transporting medium, to be interpreted below as a braided river, was consistently towards the NEE during deposition of facies association B of the Umm Ghaddah Formation (Fig. 5).

This NEE to NE fluvial dispersal deviates from the regional northward fluvial paleoflow direction prevailing in the Paleozoic as well as in the Mesozoic sequences in Jordan, where detritus were shed persistently from the south-located Precambrian basement of the Arabian Shield to the north-located Paleo- or Neo-Tethys, respectively (Amireh et al., 1994, 2001; Amireh, 1997, 1999; Amireh and Abed, 1999). This deviation can be attributed to the restriction of braided river system within the NE confined rift basins of the Umm Ghaddah Formation in comparison with extensive wide braidplains flowing northward in the Paleozoic and Mesozoic Eras.

From other point of view, the fluvial dispersal in the Cambrian Amudei Shelomo Sandstone Formation of Timna region located westward of study area (Fig. 1) is recorded by Karcz et al. (1971) to be westward. The
deviation between this paleoflow and that of Umm Ghaddah Formation can be interpreted as follows. The Amudei Shelomo Sandstone Formation is located below the marine Lower Cambrian Hakhil Formation that is equivalent to the Burj Formation in study area. Therefore, the Amudei Shelomo Sandstone Formation is equivalent to the Saleb Arkosic Formation. It is recorded by Amireh et al. (1994) the latter is exposed in the Dana–Safi area south of the Dead Sea (Fig. 1) and characterized by a rather unusual high thickness and a northwestward paleoflow. They attributed these characteristics to a synsedi-mentary subsidence that caused divergence of the prograding braidplain from the usual northward flow to a northwestern direction. Probably, this divergence of paleoflow continued westward until reaching Timna region, where braided streams were flowing to the west (Karcz et al., 1971). Timna region was probably located immediate to Dana–Safi area in the early Cambrian taking into consideration the offset of study area relative to Timna region due to Miocene-present day sinistral lateral dislocation of the Arabian plate along the Dead Sea transform fault. Another explanation can be proposed based on Bender (1974, 1982) assumption that the southern part of Wadi Arab was elevated eastern of the proposed Ediacaran rift more than western of this rift, thus detritus were shed from the elevated Precambrian base-ment westward towards Timna region.

Interbedded facies A2 (0.2–1.5 m thick) consists of cobble to fine boulder rhyolitic clasts in sandy matrix (Fig. 9c) of rhyolitic arkosic arenite type (Amireh and Abed, 2000). The mean size of the maximum 10 clasts ranges from 8 to 12 cm (Fig. 5).

Facies association B is interpreted as sand deposits of a proximal braided river flowing normal to the marginal allu-vial fan bodies, as will be discussed in the section of tectono-sedimentary evolution.

A fluvial depositional environment is interpreted because of the absence of body fossils and horizontal bedding, whereas the dominance of sandstone sheets exhibiting a unidirectional paleocurrent flow (Fig. 5) and an erosional base, and the absence of silt or mudstone deposits may indicate the braided rather than the meandering nature of the river (Rust and Jones, 1987; Brown and Plint, 1994). This interpretation of a braided river in a continental setting, inferred from facies association A, is consistent with the absence of meandering rivers in the Precambrian pre-vegetational time. This is because such vegetations would have otherwise promoted stabilization and trapping of sediments required for meandering rivers (Galloway and Hobday, 1983;
McCormick and Grotzinger, 1993; Tirsgaard and Øxnevad, 1998). Generally, in the Precambrian time, sandy to pebbly braidplain deposits were associated with alluvial fan deposits (Eriksson et al., 1999).

The major lithofacies Sp was produced by downstream migration of fields of straight-crested bedforms (sandwaves, transverse and linguoid bars) under lower flow regime conditions (Smith, 1970; Miall, 1992). Moreover, these cross-bed sets may indicate the presence of large macroforms or ‘sand flats’, that were formed in channels up to 8.5 m deep (Eriksson et al., 1999). The less common lithofacies St represents dunes migrating along the deeper part of the channel under the upper part of the lower flow regime. The laminated sandstone beds Sh were deposited at the bar tops during sheetfloods under upper flow regime conditions (Miall, 1996). The sandstone sheets were constructed by channel aggradation of fields of sandwaves, transverse and longitudinal bars and large dunes.

Upon comparing the sheet architecture and the internal stratification features of the sandstone bodies of facies association B with the modern fluvial styles, both the Platte River, Nebraska (Crowley, 1983) and the South Saskatchewan River, Canada (Walker and Cant, 1984) could be analogous. This conclusion of the Platte type of the depositing river has been also recorded in similar early Proterozoic deposits consisting of St with interbedded Sh lithofacies by Sweet (1988).

Fig. 10. Successive paleopositions of Arabia between the Ediacaran and the Devonian Periods after Konert et al. (2001). Note that Arabia reached a southerly position responsible for glaciation in the late Ordovician.

Fig. 11. Tectonic development of Arabia during the Ediacaran Period after Husseini (2000). Fracture zones formed during the Amar Collision (620 Ma) responsible for the following NW-trending Najd Fault System, and the NE-trending Oman, Dibba and Jordan Valley rifts.
5. Facies distribution in Jordan and tentative regional correlation

The facies associations A and B of the Umm Ghaddah Formation are exposed only in three localities in central Jordan, which are Wadi Abu Khusheiba, Wadi Umm Ghaddah and Wadi el Mahakra (Fig. 1). A petrographic analysis of subsurface samples of four wells (Ajlun-1 well, Hammar-2 well, Northern Highlands-1 well and Wadi Sirhan-3 well; Fig. 1) also reveals the two facies associations (Amireh and Abed, 2000). It is apparent that the Umm Ghaddah Formation occurs in certain areas within or close to the exposed Ediacaran Aheimir rhyolitic extrusion, and as far north away as in the wells Ajlun-1 and Northern High-lands-1, and Wadi Sirhan-3 eastwards (Fig. 1). These three wells are also located farther eastern away from the present day Dead Sea transform fault. The underlying Sarmuj Conglomerate is similar in origin to the Umm Ghaddah Formation, and can be tentatively correlated with equivalent deposits in adjoining countries (Table 1 and Fig. 13).

It is to be emphasized here that the following correlation attempts of the Sarmuj Conglomerate and the Umm Ghaddah Formation are tentative ones since they concern very distant deposits, although they depend on striking facies similarities, but the deposits could be indirectly dated by different techniques of radiometric dating having different uncertainties, thus the deposits may be heterochronous and the correlation could be questionable. A similar case has been recently reported by Deynoux et al. (2006) for Neoproterozoic to Cambrian glacial deposits in foreland basins of West Africa.

The Sarmuj Conglomerate can be correlated with the Elat conglomerate in the Negev region, and the Hammat Formation further westward in the Eastern Desert of Egypt (Table 1 and Fig. 13). Both are composed of a volcanic conglomerate sequence with interbedded coarse and fine clastics (Willis et al., 1988). Age of the Sarmuj Conglomerate has been constrained by Jarrar et al. (1991) between 595 and 600 Ma, which is exactly the same radiometric age of the Hammamat Formation (Willis et al., 1988). At this time age of the Hammamat Formation (Willis et al., 1988) is exactly the same radiometric age of the Hammamat Formation (Willis et al., 1988). Further southeast, it seems that there is no elastic deposit coeval to the Umm Ghaddah Formation, where the late Ediacaran-early Cambrian sequence is entirely composed of carbonates and evaporites, i.e., the Harmut Formation of the Ghabar Group of South Yemen and the Bauah and Ara Formations of the Huqf Region of Oman (AlSharhan and Nairn, 1997; Husseini, 2000; Fig. 13). In southern Iraq and Iran the Ediacaran-early Cambrian sequence is similarly constituted of an evaporite and dolomitic sequence of the Hormuz Complex (AlSharhan and Nairn, 1997; Husseini, 2000; Fig. 13).

In NW Syria, no Ediacaran deposits are known, where the deepest formation penetrated is the Lower Cambrian Zabuk Formation in the Khanaser-1 well, located north-eastern Syria (Lababidi and Hamdan, 1985). In SE Turkey, however, the Sadan Formation (Fig. 13) conglomeratic red beds considered as intracontinental rift sequence by Cater and Tunbridge (1992) might be equivalent to the Umm Ghaddah Formation.

It is apparent from the surface and subsurface distribution of the Umm Ghaddah Formation in Jordan (Fig. 12; Amireh and Abed, 2000) and the tentative correlation attempts with those in the adjacent countries (Table 1 and Fig. 13) that the formation neither occurs everywhere above the Ediacaran crystalline basement in Jordan nor it is restricted to the present day Wadi Araba-Dead Sea Rift. The same pattern of distribution is applied on the underlying Sarmuj Conglomerate.

6. Tectonic development

The study area is located at the northern flank of the Arabian Shield within the Arabia (Fig. 11). This shield was formed by a series of island arc complexes and microcontinent collisions and accretions during the time interval of about 900–750 Ma (Stoeser and Camp, 1985). At this time, it was separated from the African fragments of Gondwana by the Mozambique Ocean (Hoffman, 1999).
Then it collided with these fragments of Gondwana at the period 750–650 Ma (Abdelsalam and Stern, 1996), closing this ocean and becoming part of the northern part of the East African Orogen (Hoffman, 1999). This tectonic activity is known as the Pan African Orogeny (Kröner, 1984). Subsequently, the western margin of the Arabia (Afif terrane) witnessed a collision with the Rayn micro-plate (corresponding to central and eastern Arabia) giving rise to the N-trending “Amar Suture” between 640 and 620 Ma (Husseini, 2000). This Amar collision created an EW-directed...
compression that may have produced NW-trending fracture zone responsible for the following Najd Fault System, as well as the NE-trending fracture zone responsible for Oman, Dibba and Jordan Valley rifts (Fig. 11).

The above early cratonic phase of accretionary and collisional tectonic processes ceased in the Arabian Shield at about 620 Ma. It was replaced by an extensional collapse phase accompanied by deposition in syn-rift basins during the time interval between 620 and 530 Ma (Schmidt et al., 1979; Fleck et al., 1980; Stern, 1985; Husseini, 1989, 2000; Abdelsalam and Stern, 1996). This extensional phase was dominated by intrusions of post-orogenic alkali rich granites and rhyolites (A-type granites derived from the mantle). The extensional collapse of the Arabian Shield culminated between 570 and 530 Ma in the development of regionally extensive Najd Fault System and its complimentary syn-rift, down block-faulted, extensional basins that make up the Najd Rift System (Husseini, 2000).

Husseini (2000) defined the Najd Rift System to consist of the Najd Fault System of the Arabian Shield (Fig. 11), the Oman, Punjab and Dibba Rifts, the Zagros Fault and the Sinai Triple Junction that consists of the branches: NW-trending Najd Fault System, the EW-trending Egypt rift, and the NE-trending Jordan Valley Rift that continues to the Derik rift (Fig. 11). Fig. 11 shows the fracture zones formed during the Amar Collision prior to the initiation of the Najd strike-slip system.

The Najd Fault System is about 1200 km long and 300 km wide. Stern et al. (1984), Abed (1985) and Husseini (1989, 2000) suggested a connection between the development of Ediacaran syn-rift, extensional sedimentary basins and the Najd Fault System. These basins have a trend in agreement with that of the Najd Fault System, and are associated with abundant volcanics and dikes of the same trend. For example, in Sinai and NE Egypt, basins and dike swarms (595–540 Ma) trend NE–SW and E–W (Stern et al., 1984; Stern, 1985). Also, the Shammar volcanics in

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Fig. 13. Regional map illustrating the occurrences of the equivalent deposits to the Umm Ghaddah Formation and the Sarmuj Conglomerate in some of the Middle East countries.
Saudi Arabia and the Dokhan volcanics in NE Egypt are contemporaneous with the Najd Fault System (Stern et al., 1984).

In the study area, numerous NE trending dikes dissect the Sarmuj Conglomerate, and the overlying Hiyala Volcaniclastics (Jarrar et al., 1991), which are almost coeval with the Najd Fault System. These dikes probably indicate the existence of the NE branch of the Sinai triple junction in Jordan associated with syn-rift extensional basins. A seismic profile located south of Wadi Abu Khusheiba (in Al Jafer area, Fig. 1) (Jordan Hunt Oil Company, 1989) reveals the presence of a series of asymmetrical half-grabens bounded by listric faults in the Ediacaran and early Cambrian magmato-sedimentary sequence (Fig. 14).

The Ediacaran rifting is indicated in the study area by the following evidence: (1) presence of a series of half-grabens in the Ediacaran and early Cambrian volcano-sedimentary succession revealed by seismic data; (2) the abundance of NE–SW trending sub-parallel bimodal dike swarms corresponding to the post-orogenic extensional phase of the Pan African Orogeny (Jarrar, 1992; Jarrar et al., 1991; Beyth and Heimann, 1999); (3) the chemical features of the syn-rift volcanic sequences (alkali-rhyolite lava flows) similar to rift-related granites and rhyolites including high abundance of silica, total alkalies, REE, low abundance of MgO, CaO, Eu and transitional elements, the chondrite normalized trace element pattern, and the Nb vs. Y, Rb vs. Nb + Y and R1–R2 diagrams (Jarrar, 1992; Jarrar et al., 1993); (4) the chemical bimodality of alkaline to peralkaline character of the extrusive igneous rocks and dykes characteristic of rifting (Stern et al., 1984; Willis et al., 1988; Jarrar et al., 1992, 1993); and (5) the presence of a volcano-sedimentary succession filling intracontinental or intermontane rift-related basins and sub-basins in Jordan and adjacent countries dated at 600–550 Ma (Jarrar et al., 1991, 1993; Husseini, 1989, 2000). The rift-related volcano-sedimentary succession consists of the Sarmuj Conglomerate, the conformable overlying Hiyala Volcaniclastics, the Aheimir Volcanics, and the clastic Umm Ghaddah Formation. This succession was deposited NE–SW trending basins, as discussed below that were developed in Jordan, in response to the Najd Fault System (Fig. 12). This suggests the presence of a rift system extending NE–SW in the study area in the Ediacaran Period (Fig. 11).

### 7. Tectono sedimentary evolution

The late Ediacaran-early Cambrian Umm Ghaddah Formation is interpreted as part of the volcano-sedimentary succession that represents the extensional phase of the Pan African Orogeny. It was deposited in intracontinental rift basins, i.e., half-grabens bounded by listric faults (Fig. 15) rather than the symmetrical, full-grabens, bounded by normal faults with a down-faulted valley floor (Illies, 1981). This interpretation is based on the subsurface geophysical data and comparison with modern analogous of ancient half-graben continental rifts, such as those in the East African System (Gibbs, 1984; Rosendahl et al., 1986; Frostick and Reid, 1987).

Half-graben basins are generally characterized by: (1) a large size and great depth (Neugebauer, 1983), and unformable contact with underlying basement complexes; (2) in map view, alternating asymmetrical scoop-shaped segments, each constituting a sub-basin and separated by bedrock ridges called crossover or accommodation zones (Gibbs, 1984; Rosendahl et al., 1986; Frostick and Reid, 1987).

![Fig. 14. Seismic profile (A and B) in the southern part of the study area (Al Jafer area) carried out by JOHC (1989) indicating the presence of a series of half-grabens bounded by listric faults. For the location of profile (A and B), see Figs. 1 and 12.](image-url)
1987; Dunkelman et al., 1988); (3) a long history of vertical subsidence of the basin floor and uplift and non-deposition of the shoulders (DeRito et al., 1983); (4) a structural pattern as a combination of major listric bounding faults that form the footwall uplands, and sole in low angle deep crustal detachments, and a roll-over zone at the opposite side constituting the hangingwall lowlands which is usually disrupted by smaller antithetic and synthetic faults that lead to development of small-scale horsts and grabens (Gibbs, 1984; Rosendahl et al., 1986); (5) main boundary listric faults that tend to be discontinuous and curved in plan, and reverse in polarity along rift valleys, and are separated by transfer faults (Leeder, 1995); (6) vertical stacking of basinward stratigraphical units corresponding to major tectonic phases (Mckenzie, 1978) that consist of syn-rift sequence consisting of bimodal volcanics, coarse subaerial alluvial fan sediments, subaqueous lacustrine and/or subaerial fluvial deposits, and an overlying (post-rift) sequence of thermal subsidence phase.

The precise configuration of the basins in which the Umm Ghaddah Formation was formed is difficult to determine as there poorly exposed outcrops (Fig. 9d), and only one subsurface geophysical section is available. However, it is very likely that the basinal axis trends NE–SW (Figs. 5 and 12) reveals a NE paleoflow that is parallel to the basin margin (Fig. 15; Leeder and Gawthorpe, 1987).

(2) The NE–SW trend of the exposed Aheimir Suite volcanic belt (Fig. 12) that shed detritus to the Umm Ghaddah Formation, and is interpreted as a syn-rift volcanic sequence (Jarrar, 1992; Jarrar et al., 1992).

(3) The NE–SW distribution of the outcrop belt of facies association A in Wadi Umm Ghaddah and Wadi Abu Khusheiba. This orientation of the outcrops suggests the presence of a sub-basin that trends NE–SW-ward in Wadi Umm Ghaddah and Wadi Abu Khusheiba for 1 and 3 km, respectively (Fig. 12).

(4) The NE–SW trend of dikes cutting the Sarmuj Conglomerate that directly underlie the Umm Ghaddah Formation and has the same rift origin (Jarrar et al., 1991).

(5) This NE–SW rifting direction is in full agreement with the normal NW–SE regional crustal extension that affected the northwestern part of the Arabian Shield (Abdelsalam and Stern, 1996; Husseini, 1989, 2000).

A tectono sedimentary model for the half-grabens of the Umm Ghaddah Formation has been constructed (Fig. 15) based upon those of Leeder and Gawthorpe (1987) and Frostick and Reid (1987). Small-scale alluvial fans of a high-slope were developed at the margin of the main bounding listric fault (footwall) transverse to the rift axis,
whereas larger, transverse alluvial fans of a lower-slope formed over the roll-over zone of the hangingwall (Hooke, 1972; Leeder and Gawthorpe, 1987). Facies association A was deposited in these two sets of alluvial fans. The area between these transverse alluvial fans was occupied by an axial braided river system flowing parallel to the strike of the rift and its bounding faults (Fig. 15) that gave rise to facies association B. Similar thick alluvial fan and fluvial facies associations forming rift-basin successions have been recorded by Hoffman (1991) for the Late Precambrian Belt-Purcel Supergroups of western North America, and by Nymbe (1999) for the Ordovician-Jurassic Sinakumbe-Karoo basin, in the present mid-Zambezi Valley Basin, southern Zambia.

Sediments were transferred to these alluvial fans across the fault scarps through transverse drainage systems evolving on the footwall uplands and the hangingwall lowlands (e.g., Leeder and Gawthorpe, 1987; Frostick and Reid, 1987; Leeder, 1995), and to the central part of the basin through the axial sediment flux (e.g., Blair, 1987b; Leeder, 1995). Although the sediment flux into the central rift basin was mainly parallel to the strike of the rift and its bounding fault, the ultimate source of this axial flow was the sum of the transverse components (mass wasting and fluvial erosion) gathered from the footwall and hangingwall upland source rocks (cf. Leeder, 1995).

The entire succession of the Umm Ghaddah Formation in Wadi Umm Ghaddah (facies association A, Fig. 3) represents the transverse alluvial fan deposits accumulating at the footwall margin of the listric half-graben basin (Fig. 15). This interpretation is based on the presence of rock fall deposits (facies A1). On the other hand, profiles no. 1, 2 and 3 in Wadi Abu Khusheiba are also interpreted as deposits of transverse footwall alluvial fans of another segment or sub-basin of the half-graben rift zone (Fig. 15). Stratified, well-oriented pebbles and cobbles (profiles no. 4 and 5) may represent hangingwall alluvial fans located at the southwestern part of the Abu Khusheiba sub-basin (Fig. 15). The stratified deposits alternatively represent transverse footwall alluvial fans deposited in the distal fan by sheetflood processes.

A supply of coarse fraction was sufficient to accumulate facies association A of a small steep alluvial fan at Wadi Umm Ghaddah (Fig. 15) because numerous fault offsets and transfer zones in the footwall may have caused a larger than average alluvial fan system (cf. Crossley, 1984; Leeder and Gawthorpe, 1987; Gawthorpe et al., 1990).

The adjacent Umm Ghaddah and Abu Khusheiba sub-basins (Fig. 12) may have become linked along a structural strike when the volcanic Aheimir crossover highs were breached, enabling discharge to become axial along an NE–SW fault strike (cf. Leeder and Jackson, 1993; Jackson and Leeder, 1994) as the case of the recent Rio Grand rift of Colorado and New Mexico (Kelley, 1979; Ingersoll et al., 1990), and the Humbold River in northern Nevada (Blair, 1987b). The position of this axial stream was controlled by the encroaching transverse fans, periodic tilting, emplacement of landslide debris flows and possible intra-basinal horst structures (Leeder, 1995).

Facies A1 was deposited adjacent to the fault scarp in Wadi Umm Ghaddah and Wadi Abu Khusheiba. In Wadi Abu Khusheiba, grain size of clasts decreases from profile 1 to 5 (Fig. 4), suggesting that the alluvial fan prograded southward. Moreover, the imbrication of clasts in facies A3 and channel orientation suggest westward flow from the main bounding fault of the half-graben sub-basin (Fig. 15). Thus, the alluvial fan extended northwestward normal to the fault scarp and encroached the NE axial fluvial system located somewhere between the two profiles. This NE direction of the fluvial system is indcited from the paleocurrent data obtained from facies association B in Wadi el Mahraka (Fig. 5).

Therefore, the Wadi Umm Ghaddah, Wadi Abu Khusheiba and Wadi el Mahraka half-graben sub-basins in which the Umm Ghaddah Formation was deposited had a NE–SW orientation (Figs. 12 and 15). A similar marginal alluvial fan and axial river system filling a half-graben basin is recorded by Blair (1987b) for the Jurassic-Lower Cretaceous Todos Santos Formation, Chiapas, Mexico and the Devonian Munster basin, Ireland (MacCarthy, 1990).

Sedimentation in extensional basins generally is controlled by interplay of: sediment input, faulting and block rotation that creates tectonic slopes and topography, subsidence and tectonic changes. Furthermore, the study of modern alluvial fans reveals that sedimentation is controlled by both allocyclic variables, such as climate and tectonism, and autogenic variables, such as channel diversion and bar migration that are related to the fan depositional system (Hooke, 1972; Schumm, 1977). These variables will be employed to interpret the cyclic sedimentation through the Umm Ghaddah Formation.

The Umm Ghaddah basinal sequence is characterized by several minor coarsening and fining upward sequences, but there is an overall or a large-scale fining upward tendency (Figs. 3 and 4a and b). Such cyclicity may reflect a fault-controlled tectonic movement through the time of the Umm Ghaddah Formation.

Some of the coarsening upward sequences result from the occurrence of proximal debris flow deposits above distal sheetflood deposits as the upper part of section no. 1 (Fig. 9b), central part of section no. 2, the entire profile no. 3 in Wadi Abu Khusheiba (Fig. 4a and b). Other coarsening upward sequences are observed within the sheetflood deposits as the case in the central and uppermost portion of profile no. 5 in Wadi Abu Khusheiba (Fig. 4a and b).

These coarsening upward sequences could be attributed to fan progradation (Ramos et al., 1986), and to tectonic uplift of the adjacent basement (Heward, 1978; Gloppen and Steel, 1981; Ramos et al., 1986) as the case in most alluvial fan sequences (Blair, 1987b).

The fining upward trend is observed within the lower part of Wadi Umm Ghaddah, where it displays three of such sequences (Fig. 3), and the upper portion also exhibits
another sequence. The central part of the Umm Ghaddah Formation in Wadi Abu Khusheiba is characterized by a fining upward trend in all the studied five sections (Fig. 4a and b). This fining upward cyclicity resulted from a vertical change in fan subenvironments from proximal debris flow (facies A2) to distal sheetfloods (facies A3, A4, b; Fig. 15; Heward, 1978), and due to gradual abandonment or retreat of fan lobes (Gloppen and Steel, 1981) coupled with tectonic quiescent intervals (lower fining upward cycle at profile 2 in Wadi Abu Khusheiba).

The overall (large-scale) fining upward tendency of the Umm Ghaddah Formation in the type locality (Fig. 3) could be attributed to the gradual cessation of the tectonic uplift associated with an increase in active fault subsidence, and consequent transgression of fine-grained sediments to fill the basin (cf. Nyambe, 1999). Moreover, this overall fining upward tendency reflects the fact that the source area relief became subdued (Howard, 1966) following the high relief of the source terrain at the beginning of the Umm Ghaddah time. This high relief is indicated by the thickness and coarse grain size of the terrigenous detritus of facies association A (cf. Mack and Rasmussen, 1984).

Only in the Wadi el Maharaka outcrop, and in the subsurface AJ-1 well (Amireh and Abed, 2000), the basin-margin alluvial fan (facies A2) and the basin-axis fluvial deposits (facies association B) are found vertically stacked (Fig. 8b), but without showing any trend of cyclicity. This stacking may indicate that periodically the basin-axis braided river occupied the basin-margin and that at other times alluvial fan deposition took place there (Blair, 1987b). During tectonic subsidence, fluvial system was initiated at basin margin due to creation of a topographic depression, rather than to a phase of tectonic quiescence (Blair, 1987b). Subsequently and aided by the lower rate of tectonic subsidence, the fan prograded and displaced the fluvial environment basinward (Blair, 1987b). In this depression the sand flats of the Umm Ghaddah braided river aggraded vertically to give rise to the high thickness of facies association B, that attained 900 m in NH-1 well (Amireh and Abed, 2000). This might also reflect a high rate of erosion in the uplifting hinterlands and a high axial sediment influx (Leeder, 1995).

8. Palaeogeography

Facies associations A and B of the Umm Ghaddah Formation were deposited under terrestrial conditions in several isolated half-graben sub-basins (Figs. 12 and 15). In the Ediacaran–early Cambrian, terrestrial conditions dominated over the study area, central and northwest of the Arabian Shield, whereas marine conditions affected the northeastern and southeastern portions of Arabia, which were inundated from the Asiatic side of the Paleo-Tethys Ocean (Fig. 11; Husseini, 1989; AlSharhan and Nairn, 1997).

Fig. 12 is a paleogeographic/paleotectonic map showing the distribution, arrangement of the half-graben sub-basins including the Wadi Umm Ghaddah-Abu Khusheiba sub-basin and Wadi el Maharaka sub-basin, the Aheimir Volcanic Suite swell, a series of half-grabens revealed by seismic study in the Al Jafer area that are filled with Umm Ghaddah and other Ediacaran clastics and alkaline volcanics, and the present day Dead Sea transform fault. Since these volcano-clastic successions, besides the underlying sequence of the Sarmuj Conglomerate–Hiyala Volcanics and the Aheimir Volcanics represent syn-rift deposits, as interpreted above and as recorded by Jarrar et al. (1991, 2003), respectively, it can be concluded that a rift system trending NE–SW existed in the study area in the Ediacaran Period. According to the available surface and subsurface data, it is not possible to determine the width of this rift system. This inferred rift could be in continuation with the Derik rift in SE Turkey recorded by Husseini (2000), and supports the presence of the Sinai triple junction proposed by the latter.

It is obvious from Fig. 12 that the direction of the Ediacaran half-graben basins and consequently the Ediacaran rift is oblique to that of the present Dead Sea transform fault. Moreover, the sub-basins in the Al Jafer area are far away from the location of the present day Dead Sea fault. The same is applied to the subsurface basins of Wadi Sirhan (WS-3 well), Ajlun (AJ-1 well) and Northern Highlands (NH-1 well) that are also remote from the Dead Sea transform fault (Fig. 1).

Therefore, the Ediacaran rift system differ in trend from the present Dead Sea transform fault and extends to areas much eastern of it, suggesting that this late Precambrian rifting phase could not be related to the present day Wadi Araba-Dead Sea rift as proposed by some authors.

9. Conclusions

Outcrop, subsurface and laboratory data reveal the relationship between alluvial depositional systems and tectonic control for the late Ediacaran–early Cambrian Umm Ghaddah Formation in Jordan.

The Umm Ghaddah Formation was deposited in extensional fault-controlled basins and sub-basins analogous to intracontinental half-grabens with listric-fault margins. The basin-fill succession consists of marginal alluvial fans that drained towards the northwest from the NE–SW trending, major bounding listric fault, and encroached upon an axial braided fluvial system flowing northeast parallel to the margin of the half-graben basin. The alluvial fan facies association exhibits a characteristic development from proximal facies (A1 and A2) to distal facies (A3 and A4). Facies A1 and A2 were deposited by rock falls and non-cohesive debris flows of the sediment gravity flow processes, respectively, whereas facies A3 and A4 represent sheetflood deposits.

The Umm Ghaddah Formation was dominated by vertical subsidence and uplift expressed in various types of cyclicity. One large-scale fining upward cycle is attributed to gradual waning of the final phase of the Pan African
Orogeny, whereas several smaller scale, coarsening and fining upward cycles indicate minor tectonic pulses and autocyclic shifting of alluvial fan-building processes.

The Umm Ghaddah Formation is interpreted as a syn-rift depositional sequence which together with underlying Ediacaran Aheimir Volcanics, and Hiylia Volcani-clastics–Sarmuj Conglomerates could prove the existence of a rift system in the study area in the Ediacaran Period related to the Najd Fault System. The distribution of the surface and subsurface occurrences of the Umm Ghaddah Formation in Jordan which is not restricted to the vicinity of the present day Wadi Araba-Dead Sea transform fault may indicate that the late Precambrian rifting phase may be not related to the present day Dead Sea transform fault.

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