Mitt. Geol.-Paläont. Inst. Univ. Hamburg	Heft 59	S. 167–188	Hamburg, Dezember 1985

Origin and deposition of phosphate ores from the Upper Cretaceous at Ruseifa (Amman, Jordan)

KLAUS BANDEL, HAMBURG,
and SHAKER MIKBEL, AMMAN*)

Mit 20 Textabbildungen

Dedicated to Prof. Ehrhard Voigt
on the occasion of his 80th birthday,
July 28, 1985

Inhaltsverzeichnis

---

*) Anschrift des Verfassers: Prof. Dr. Klaus Bandel, Geologisch-Paläontologisches Institut und Museum, Univ. Hamburg, Bundesstr. 55, D-2000 Hamburg 13, F. R.-Germany.
Dr. Shaker Mikbel, Department of Geology, Univ. of Jordan, Amman, Jordan.

Abstract:

The 4 phosphate beds of economical value at the Ruseifa Phosphate Mines are deposits of the shallow sea, Maastrichtian time. Phosphoritic sand is composed of grains of skeletal and diagenetic origin which had formed and accumulated in marine muds of Amman Formation (of predominately Campanian age). Fecal pellets were altered into phosphorite in marine deposits during early diagenesis from Upper Ain Ghazal Formation (Coniacian) onwards. The Ruseifa phosphates formed when Amman Formation was eroded along an island chain that accompanied the Ruseifa fault and folds associated with it. Phosphatic sands were winnowed and concentrated into off-shore tidal and subtidal sand-bars.

Zusammenfassung:

Die 4 oberkretazischen Phosphatflöze der Phosphattagebaue von Ruseifa, die von ökonomischem Wert sind, entstanden im Flachmeer. Der Phosphatsand besteht aus Skelettelementen und während der Diagenese entstandenen Körnern, die sich ursprünglich in den Meeresschlammen der Amman-Formation (vornehmlich Campan) bildeten. Phosphatisation von Kotpillen in marinen Ablagerungen während der frühen Diagenese ist im Untersuchungsgebiet bereits seit der oberen Ain Ghazal Formation (Coniac) eingetreten und setzte sich bis in die Ruseifa-Formation (Maastricht) hin fort. Die Phosphate von Ruseifa entstanden, als Sedimente der Amman-Formation im Bereich einer Inselkette abgetragen wurden, die entlang der Ruseifa-Störung und mit ihr verbundener Falten entstand. Phosphatsand wurde ausgespült und vor der Küste zu Sandbänken zusammengewaschen.

1. Introdoction

To the east of Amman, in the area of Ruseifa, phosphates have been exploited for the last 40 years. They are concentrated in 4 thick beds which at first were mined in the subsurface but later in open pit mines which now riddle the area along with hills from overburden waste. A range of hills rises just a few km to the south of exploitable deposits and the mines. Its origin is connected to the Ruseifa fault representing a major structural element considered as the Suweimi-Amman side branch of the Jordan rift by WIESEMANN (1969). Ruseifa fault connects to the rift system at the NE corner of the Dead Sea. It passes through southern Amman and is continuous up to the vicinity of Qasr El Hallabat ending to the east of it below younger volcanic rocks of the Azrak area.

The phosphate-bearing Ruseifa Formation ("phosphorite unit" of BENDER, 1968) is underlain by the Amman Formation ("silicified limestone unit" of BENDER, 1968). Both formations differ from other Upper Cretaceous rocks in Jordan not only by the presence of many chert layers but also by their higher content of phosphatic grains. Synsedimentary folds as can be noted at Jebel Hussein as well as along the slopes of the Wadi Zarqa in downtown Amman to the Ain Ghazal area are common in Amman Formation. They show amplitudes of 10 cm to 10 m. The large folds concentrated in the lower Amman Formation in their origin are related to the dehydration of the marly chalks during diagenesis of the Ain Ghazal Formation. Folding is evidence for some structural unrest and earth quakes during deposition of Amman and Ruseifa Formations (Campanian to Maastrichtian time). With the beginning of deposition of Ruseifa Formation unrest increased resulting in visible displacement of blocks and lifting of sea bottom above sea level. In the hills to the south of Ruseifa mines Ruseifa fault forms the margin of a lifted block and shore deposits of the Ruseifa Formation formed. Near Tel Es Sur (Fig. 2) sections were measured to the east and west and on both sides to the north and south of the Ruseifa fault. Beds were correlated to those present in the area of the mine, so that the depositional history formation of the phosphatic ores could be reconstructed.

The field study was carried out as part of the German-Jordanian cooperation in geosciences between the University of Amman and the University of Hamburg.

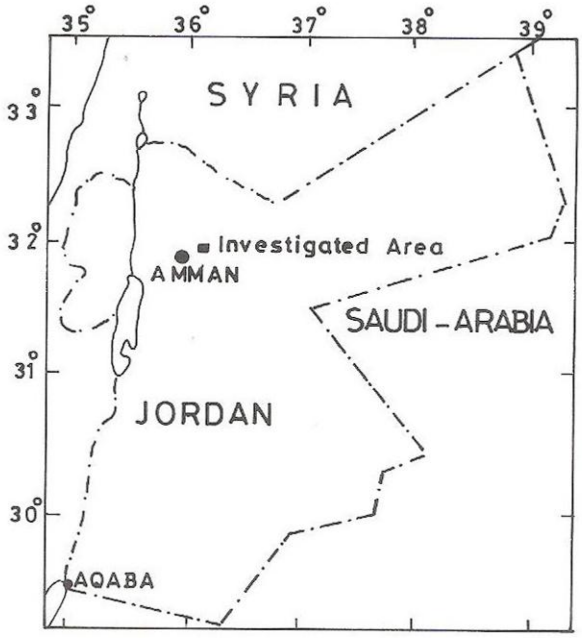


Fig. 1 Map of the area that was studied in detail. The black rectangle in the sketch of Jordan indicates its position NE-of Amman. Detailed map of the area indicated in Fig. 1.

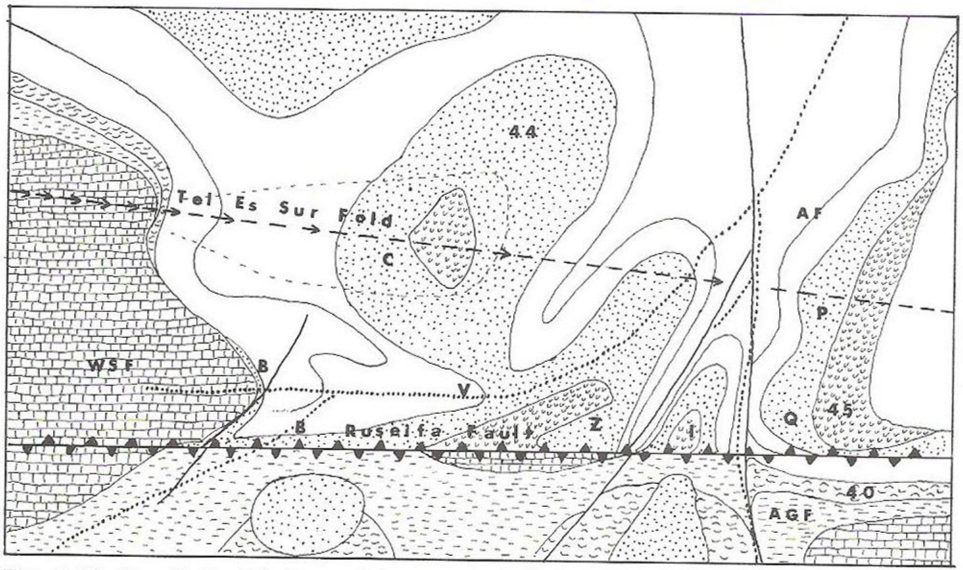


Fig. 2 The Ruseifa Fault in the south is accompanied by Tel-Es-Sur Fold in the north. Rock units from oldest to youngest are: limestones of the Wadi Sir Formation (WSF); chalks of the Ain Ghazal Formation (AGF), oyster-bearing member 40 (40) of the chert-rich Amman Formation (AF); and Ruseifa Formation with lower phosphorite member 44 and upper oyster limestone member 45.

The Ruseifa fault enters the studied area from the east cutting off the oyster-bank deposits at the Roman quarries (section Q and P) (Fig. 2, 9). It crosses the wadi and is crossed by minor faults arranged almost vertically to it. These faults commence a bit to the north and the wadis follow them. The zone cut out in this way is shown in Fig. 2 (section I). Ruseifa fault in this section displaces Amman Formation in bringing it into contact with Ain Ghazal Formation at exposed surface. Ruseifa fault then cuts through a hill displacing oyster beds of the Ruseifa Formation against Ain Ghazal chalks and the lowermost oyster beds of Amman Formation (member 40). To the west of the oyster limestone the fault is connected to beach deposits of Ruseifa Formation (Fig. 13, 14). At the end of the small wadi, that runs almost parallel to the Tel Es Sur ridge in the south, Ruseifa fault enters Wadi Sir Formation displacing massive limestone beds against similar rocks. At the Wadi Qattar the fault is connected to a well exposed fold (Fig. 18). The Tel Es Sur fold that accompanies Ruseifa fault to the north dips towards the east with its axis until at the highest altitude of Tel Es Sur the dip reverses towards west.

B. Section near Ruseifa (R) (Fig. 4)

The Ruseifa Formation with its 4 exploitable phosphate beds and the units below and above them is well exposed near the old phosphate mines at the southern slope of Wadi Zarqa in Ruseifa (section R).

The base of the lowest bed (1) consists of limestones intercalated with phosphatic sand. Here burrows of crabs of the *Ophiomorpha*-type have been excavated from the

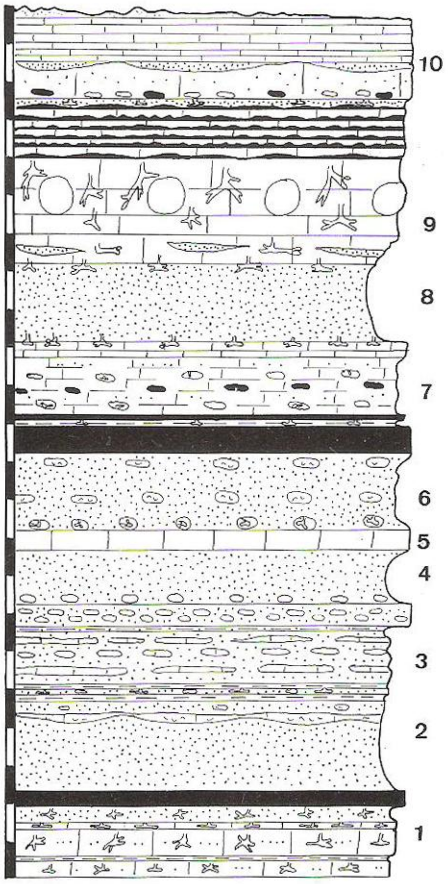


Fig. 4 Section R. Description see text. Each bar represents 1 m.

2. Geological setting

With the Cenomanian transgression onto Lower Cretaceous sand- and siltstone of the Kurnub Group the sea covered an area formerly characterized by coastal and fluviatile deposits (BANDEL, 1979; ABED, 1982). No longer sand and silt from terrestrial source reached the shallow sea that covered the central and northern parts of Jordan. The shore lay in the south and southeast of Jordan and remained here throughout the Upper Cretaceous and Lower Tertiary times. Calcareous material mixed with more or less clay characterizes Cenomanian and Turonian beds forming an about 450 m thick column of limestones and marls (BENDER, 1968; BANDEL and GEYS, 1985; BANDEL and WIEDMANN, 1986).

During Coniacian time chalky marls and chalks of Ain Ghazal Formation (Fig. 3) were deposited in the whole area.

The following Amman Formation near Ruseifa measures about 25 m, while in Amman and Ain Ghazal it is about 40–80 m thick. This difference is probably due to erosion of the upper Amman Formation before emplacement of Ruseifa Formation.

Within the uppermost beds of the Ain Ghazal Formation (Member 39; BANDEL & WIEDMANN, 1986) (Fig. 3) the productivity of the sea water changed. While the calcareous muds of the late chalk and limestone beds were deposited currents loaded with more P and Si than before reached the area. This increase of P and Si can probably be correlated to upwelling currents from the depth of the Tethys ocean in the north now

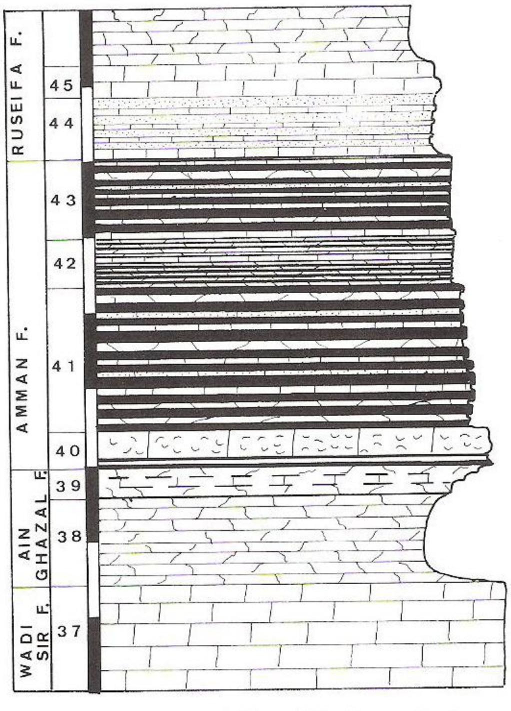


Fig. 3 Columnar section through the upper 90 m of the Upper Cretaceous rock sequence as it is found in the Amman-Ruseifa area. Turonian limestone of Wadi Sir Formation (member 37) are overlain by chalky Ain Ghazal Formation with member 38 and 39. Member 39 contains Coniacian ammonites. The chert (black signature), chalk, limestone intercaltion of Amman Formation begins with the oyster limestone (member 40). Ruseifa Formation is of Maastrichtian age and bears phosphorite beds together with chalky, limy, cherty intercalations (member 44) and ends with limestone often composed of oysters and their debris (member 45). This sequence is overlain by the "chalky marl unit" of BENDER (1968). Each black or white bar represents 10 m.

carried into the shelf sea. Many organic fecal pellets now became transferred into phosphorite within the muddy bottom substrate during early diagenesis. Phosphate-rich elements like bones, teeth and scales of vertebrates in the same process were phosphate-enriched. This transformation into solid phosphatic particles was rapid and happened within soft surface mud so that, wherever currents carried away clay-sized particles remaining sand to a large extent consisted of such former fecal pellets.

Transformation of fine-grained beds into chert, in contrast, occurred much later during diagenesis when beds were covered by several metres of sediment. During the deposition of Amman Formation in the area under discussion, silicified beds were not uncovered by erosion. Where sliding and synsedimentary folding occurred and beds came to the surface of the sea bottom that lay in several metres depth, no chertisation was present. Winnowed sand beds commonly also contained small molluscan shells. These were still of aragonitic composition and commonly very delicate when freshly reworked from the limy muddy bottom and enriched in the phosphatic sand. Later on, these shells were transferred into silica (BANDEL, 1982) or totally disappeared due to dissolution.

While phosphatic sand and fine gravel are less common than chert, limestone and marl in the Amman Formation, they form a dominant portion of Ruseifa Formation. This change in composition is not due to a change in the chemistry of the sea water, but it is connected to structural unrest at Upper Campanian time. Now almost flat sea bottom was transferred into a more rugged topography of which higher parts became exposed to erosion while the actual sea shore remained far to the south. Deposits of Ruseifa Formation are, therefore, of variable thickness and composition. After structural unrest the sea again flooded all the area and covered it by new calcareous, marly and silica-rich deposits ("chalk marl unit"; BENDER, 1968).

3. Section and field studies in the Tel Es Sur area, Ruseifa

A. Structure

The morphology of the Tel Es Sur area is the result of the presence of an anticline found in limestones of the Wadi Sir Formation (Fig. 3) (massive limestone unit of BENDER, 1968). The hill chain of Tel Es Sur exposes such limestones for about 2.5 km length. Maximum elevation of the Tel Es Sur fold forms the highest topographic peak of 820 m and fold axis runs from 650 N to 820 S. To the south the anticline is accompanied by minor folds with much lower amplitude. The Tel Es Sur anticline is asymmetric with its southern flank cut by a major thrust fault. In the investigated area (Fig. 2) both anticlinal flanks dip with about 20° to NW or SE, while near Wadi Qattar the SE flank is vertical to overturned (Fig. 18). The SE block has been raised in relation to the NW block on a fault in the crystalline basement, and the sediments of the southern block have been thrusted somewhat over those of the northern block, bending them and pushing them up (Fig. 9, 15). As is shown further below, this movement was active in the Upper Campanian, and recent topography as well as subrecent deposits in the wadis indicate that the structure has been active from time to time up to our time.

The Tel Es Sur area is part of the Amman-Hallabat structure (MIBEL & ZACHER, 1981) which is 70 km long and has been described as Suweimi-Amman-Ruseifa fault by WIESEMANN (1969). The later author connected it to the main faults of the Jordan Rift, but the Amman-Suweimi-Ruseifa fault system is much older than the modern rift. Along the rift the fault zone holding Ruseifa fault has been displaced for 110 km to the north so that its continuation is found 110 km to the south on the western side of the rift (BANDEL, 1981). SHILONI (1981) reported a similar structure south of Beer Sheva which is also connected to phosphate fields. It could lie at about the continuation of Ruseifa fault to the SW if translation displacement in the rift were absent.

limy mud and filled with phosphatic sand. They reach 15 cm below the sand surface. This intercalation ends with a laminated chert bed. In it some layers show mud cracks which formed when the limy mud fell dry.

A bed of soft, phosphatic sand (the first phosphate seam) (2) ends with limestone pebble and intraclast layers (3). Some of these pebbles contain a rich molluscan and vertebrate fauna, others represent reworked lime-mud balls without fauna. Continuous clay- and lime-mud layers have become disintegrated by mud cracking and burrowing crabs. Intraclasts with upturned sharp edges were transported and round mud balls formed when layers were reworked.

The second phosphate seam (4) begins with a layer of up to 15 cm large micritic limestone-mud balls. A fossiliferous limestone (5) separates it from the third phosphate seam (6). Again limestone pebbles penetrated by up to 2.5 cm wide crab burrows are present in several layers. In an upper one of these limestones a rich fauna of ammonites, bivalves and gastropods is found. The phosphate sand holds numerous well preserved vertebrate remains.

The zone between the third and the fourth phosphate seam (7) is characterized by bioturbated marly shale and chert with thin layers of phosphatic sand. Some clay-rich beds contain connected fish skeletons. From the base of the fourth seam (8) up to 1 cm wide crab burrows have been excavated into the beds below and have been filled with sand. The phosphate sand holds many vertebrate bones and has partly retained its original cross bedding structures.

Chalky massive and laminated limestones follow with large concretions of sugar-grained limestone holding uncompacted crab burrows (9). Carbonate sand consist of oyster-shell debris and is also found in small channels, here with cross bedding preserved.

The top of the section (10) consists of an intercalation of laminated chalk with many remains of fish and laminated, stromatolitic chert beds. It is overlain by oyster-debris sand that contains mud balls and small channels. Complex crab burrow systems excavated from the sand partly remained unfilled displaying tunnels of up to 2.5 cm width that connect chambers of up to 6 cm width with each other. A thin bed of phosphatic sand ends the section.

C. Section at the north flank of Tel Es Sur anticline in Wadi Qattar (M) Fig. 5)

Below base of the section and in its lower part (1) an intercalation of phosphatic sand and fine-grained chert layers is developed. Sand beds are graded and commonly pebbles or intraclasts are present overlying chert with irregular surface. They laterally often change their thickness. Chert is often fragmented by bioturbation. Chert beds may also be composed of intraclasts or breccia-like components. This brecciation occurred after bioturbation and is probably due do differential compaction affecting the fine-grained beds in a different way from the sand. When shrinkage cracks formed in the former limy mud, the sand above was still mobile and flowed into the cracks and fissures. Other chert layers show more or less undisrupted lamination. Many chert-bed surfaces are covered with silicified fossils representing a varied fauna of baculitids, ammonites, fish bones and teeth, nuculid and pholadid bivalves and different species of mud-living gastropods.

A bed of brecciated chert ends a series of graded phosphate beds separated from each other by layers of chert intraclasts. These have formed due to the disintegration of fine-grained beds by bioturbation. The upper phosphate bed contains many oyster shells and shell fragments. Some layers contain chert-mud balls. Bioturbation here and there is well visible, usually as *Ophiomorpha*-like crab burrows filled with sand.

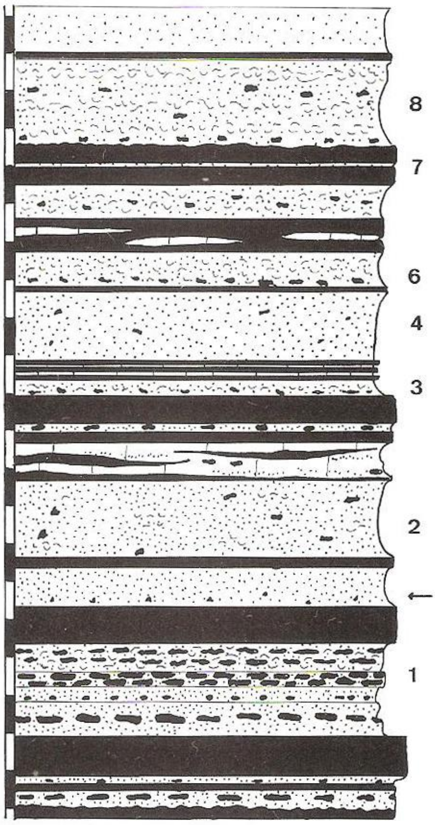


Fig. 5 Section M. Description see text. Each bar represents 1 m.

A bed that can be correlated to the first phosphate seam in section R follows (2) and is separated from a second phosphate seam by a chert bed that has been penetrated by numerous tunnels of crab burrows which have subsequently been compacted to half their original hight. The phosphate sand holds fragments of oysters and below 5 mm large chert fragments derived from uncovered and eroded chert layers (arrow). The upper phosphate sand contains such angular chert of up to 10 mm.

Chert beds intercalated with phosphatic sands show well developed desiccation features. A polygonal meshwork of mud cracks is present. Crack margins commonly are twisted upwards and sheet cracks below surface follow bedding planes demonstrating that mud surface was baked in the sun and lay in the intertidal regime of the shore. Laterally beds with sheet cracks and mud cracks may change into cherts without these features that were deposited just below the tidal flats (3). Phosphatic sand covered intertidal mud, filled cracks and was burrowed down by crabs. Sand deposition occurred when currents were strong. They were able to pick up dried mud chips and to deposit them elsewhere as intraclast layers. Currents also eroded mud beds and redeposited their remains in mud-ball layers. The sandy sediment itself was totally churned by infaunal organisms (4). Larger burrowers, like crabs, commonly also displaced mud chips and mud balls from their original position and dug tunnels through them. The oyster-shell debris is mixed with the sand as well as angular chert particles usually smaller than 1 cm (6).

In the uppermost phosphate bed (8) oyster shells, intraclasts and crab burrows reaching 25 cm down (7) and with 2 cm wide tunnels are common.

D. Sections near the Roman quarries (P and Q) (Fig. 7, 8)

Near small quarries where columns of oyster limestone were manufactured at Roman time, two sections, only about 100 m apart from each other were measured. When compared to each other they show the rapid lithological change occurring when the Ruseifa fault is approached. Limestones intercalated with discontinuous chert layers in section P (Fig. 7) are represented by chert intercalated with phosphatic beds in section Q (Fig. 8) (1). Many of these beds belonging to the Amman Formation contain baculitid ammonites as well as bivalves and gastropods (1). Deposition of sediment and first steps of diagenesis occurred under submerged conditions. The lateral change of facies is due to the transition of fine or less fine carbonate muds which were settled by a benthic soft bottom fauna that destroyed original sedimentary structures. Winnowed muds revealed phosphatic particles and shells. Some mud beds were compacted before their surface was uncovered by erosion. Burrowing crustaceans excavated their tunnels into them.

With the beginning of Ruseifa Formation (2) erosion is more evident. Chertizised former mud beds are intercalated with phosphatic sand in section P while in section Q sand holds reworked mud beds in shape of mud-ball layers and mud intraclasts. Mud-cracked beds and intraclast layers increase in number, indicating that muddy bottom substrated periodically fell dry and became sun-baked.

The next event changing sediment composition is the time when erosion of the emerged Amman Formation just south of the Ruseifa fault reached the level in which fine-grained beds have been diagenetically silicified. Chert beds disintegrated into angular clasts of usually less than 1 cm in diameter which became mixed with the coarser pebbles of the phosphate sand (arrow). Angular chert intraclasts are coarser in section Q (over 1 cm) than in P (less than 1 cm). Mud-cracked beds form continuous chert banks in section P, while in section Q they have disintegrated into intraclast

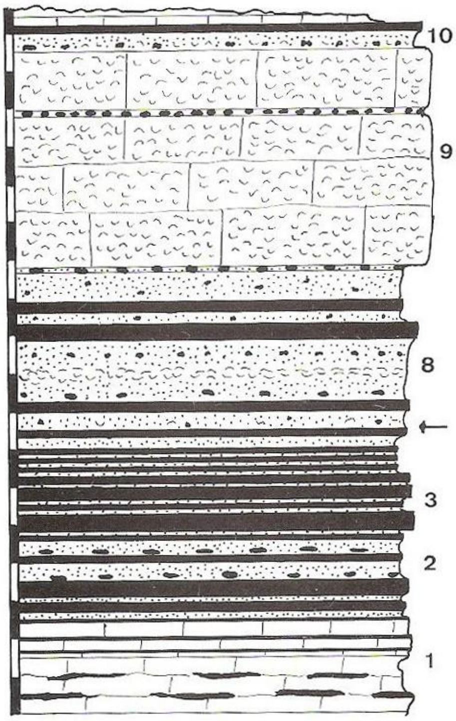


Fig. 7 Section P. Description see text. Each bar represents 1 m.

layers or mud-ball layers. Oyster coquinas are present in both sections (8) and are bioturbated with burrows of crabs that also penetrate mud layers, mud intraclasts, or mud balls.

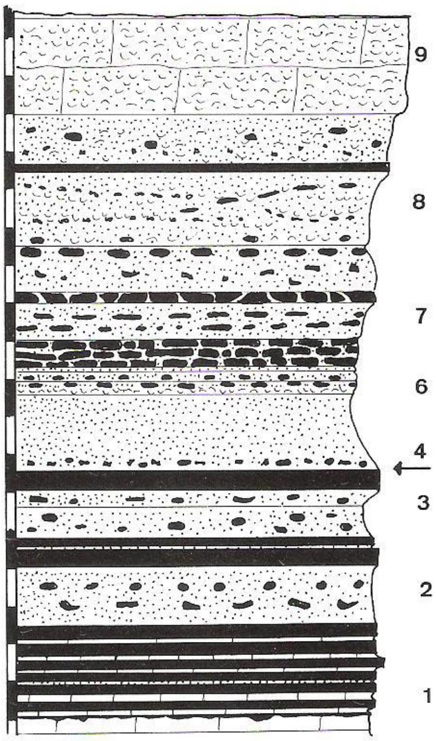


Fig. 8 Section Q. Description see text. Each bar represents 1 m.

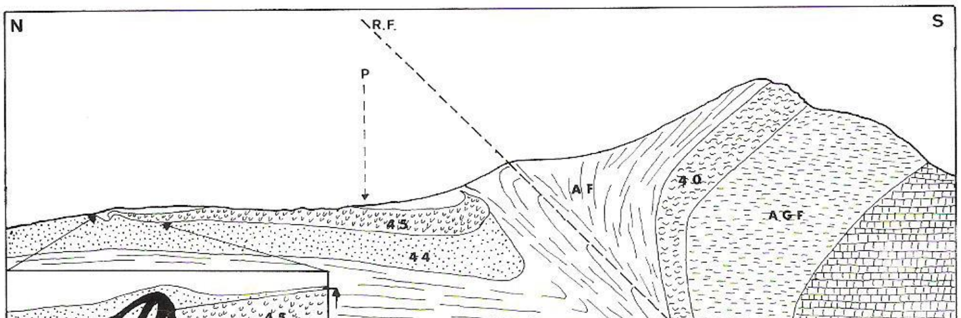


Fig. 9 Sketch of Ruseifa Fault (RF) as it is seen near the Roman quarries. The oyster bank (member 45 of Ruseifa Formation) ends with a synsedimentary fold developed in the phosphoritic sands and chert layers below (44/45). AF: members 41 to 43 of Amman Formation; 40: oyster-rich limestone of member 40; AGF: Ain Ghazal Formation; WSF: limestone of the Wadi Sir Formation.

An oyster bank, in section P, did not reach section Q lying shoreward of it. It formed a lenticular body of about 180 m in width and a maximum thickness of 5 m, that in seaward direction grades into phosphatic sands.

After deposition and induration of the oyster-shell bank a synsedimentary fold formed at its northernmost, seaward edge (Fig. 9) This fold affected about 4.5 m of sediment below the oyster limestone and it formed before phosphatic sands covered the oyster bank. Ejected water deformed the mud beds while sand flowed before the mud beds silicified. Folding may have been triggered by earthquakes which accompanied the formation of Tel Es Sur Island.

In three phosphatic beds just below the oyster limestone from location of section Q to the Ruseifa fault the size and the amount of pieces of angular chert increases towards the fault. During this deposition the beach lay only a few tenth of metres away, either directly at Ruseifa fault or a little south of it.

E. Section I (Fig. 10)

The small valley passing the Roman quarries uphill splits into two, reflecting the course of faults vertically to Ruseifa fault. Between branches section I lies close and just north of Ruseifa fault. To the south of Ruseifa fault Ruseifa Formation overlies Ain Ghazal Formation directly and Amman Formation has been totally eroded (Fig. 15). The oyster bed of lower Amman Formation (Member 40) comes to the surface further to the south. Ruseifa Formation overlies Ain Ghazal and Amman Formation with a clear angular unconformity (Fig. 15).

The section I just to the north of Ruseifa fault exposes similar sediments as seen in section P and Q to the east and section Z to the west. Greater thickness of lower beds of Ruseifa Formation in Section Z indicates that, during the deposition of these sediments, not only Ruseifa fault was active but also the minor faults vertically to it.

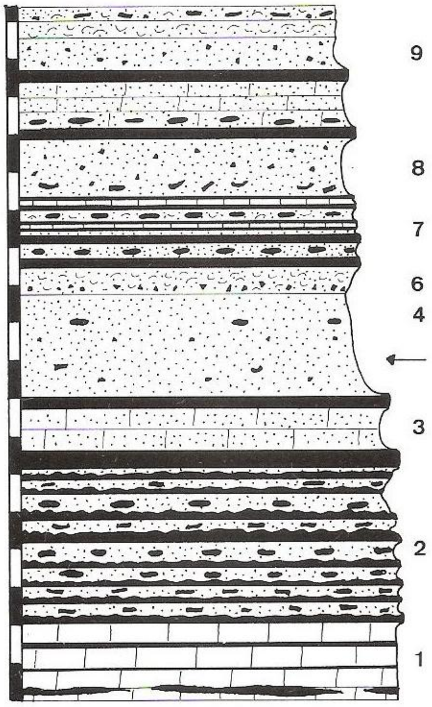


Fig. 10 Section I. Description see text. One bar represents 1 m.

The lower Ruseifa Formation in section I is similar to that of section P and Q. Chert beds with corroded upper surface are intercalated with phosphate sands containing mud balls and angular intraclasts at their base (2). Eroded chert fragments from Amman Formation co-occur with an oyster coquina (from arrow). Oyster-bank beds are not developed, only layers with more or less worn oyster shells. Calcareous sand is largely derived from eroded oysters (9).

F. Section Z (Fig. 11)

Opposite to the Roman quarries, on the western slope of the wadi, Ruseifa fault displaced the first bed with chert breccia below exposure surface, but these beds are completely exposed just to the north, away from the fault, here overlying Amman Formation (Fig. 12). The lower beds exposed near the fault show oyster shells in phosphatic sand. Some mud balls found in these beds contain baculitid ammonites (4), thus demonstrating that fine-grained beds of upper portions of Amman Formation were not silicified when they became eroded, but at the same time chert beds were eroded nearby so that chert fragments were deposited (from arrow upward). Limestone and laminated chert intercalated with graded phosphate sand follows (5). Chert beds commonly are mud-cracked and have been compacted into large angular clasts. Some chert beds are penetrated by well visible crab burrows filled with phosphatic sand.

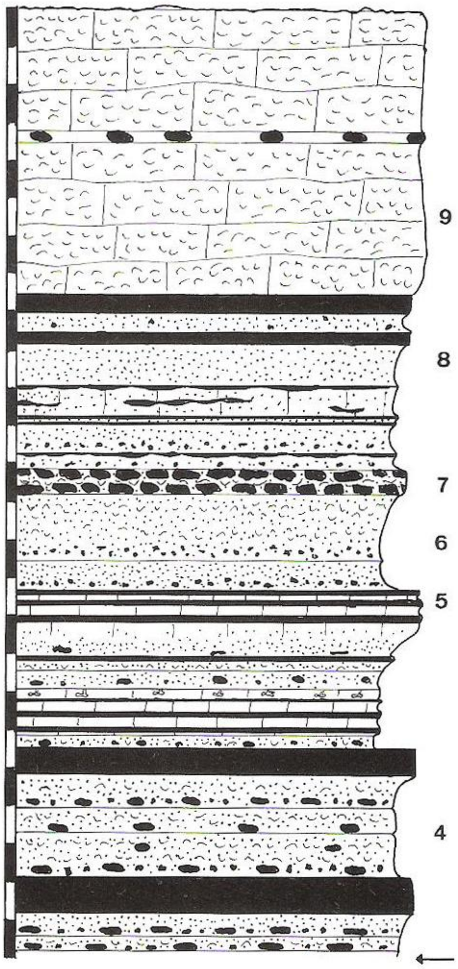


Fig. 11 Section Z. Description see text. One bar represents 1 m.

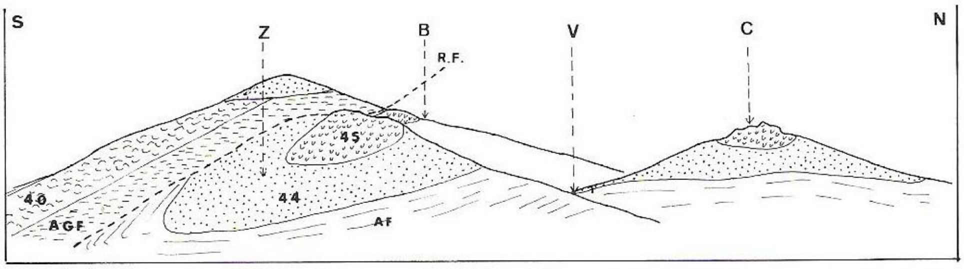


Fig. 12 View from the Roman quarries to the west. RF: Ruseifa Fault; Z: location of section Z; B: location of beach section B; V: section V; C: location of section C on top of the ancient citadel; AGF: Ain Ghazal Formation; 40: oyster-rich limestone at the base of Amman Formation; AF: Amman Formation; 44: phosphoritic sands of lower Ruseifa Formation; 45: oyster-limestone of Ruseifa Formation.

Above (6) oyster debris is more common and chert layers may consist of mud ball intercalations in phosphate sand (7). Some chert beds show fine stromatolitic and parallel lamination. Mud cracks and sheet cracks as well as burrow systems of crustaceans are present. The top of the section (9) is formed by almost 9 m of oyster limestone with some phosphate sand layers in the lower portion and chert intraclasts in the upper portion. A layer of mud balls separates both units.

G. Beach sections (Fig. 13 and 14)

Just to the west of section Z (Fig. 12, B) and the oyster-bank limestones beach deposits are exposed just north of Ruseifa fault and only several metres away from it. Beds consist of coarser angular to subrounded chert pebbles which grade into calcareous sand away from the Ruseifa fault (Fig. 14). This facies change from chert gravel, mud ball and subrounded mud chip-strewn beaches to tidal and subtidal sand is rapid. 7 m from the gravel beach sand contains only small angular chert fragments. While beach sand is mainly calcareous, sand of the off-shore bars and the infralittoral fringe is mainly phosphatic.

Beach deposits can be followed to the west where they continuously overly older beds (Fig. 13). While just NW of section Z (Fig. 11) in section V (Fig. 16), about 27 m of Amman Formation form the base, only 50 m further west oyster beds of the lowermost

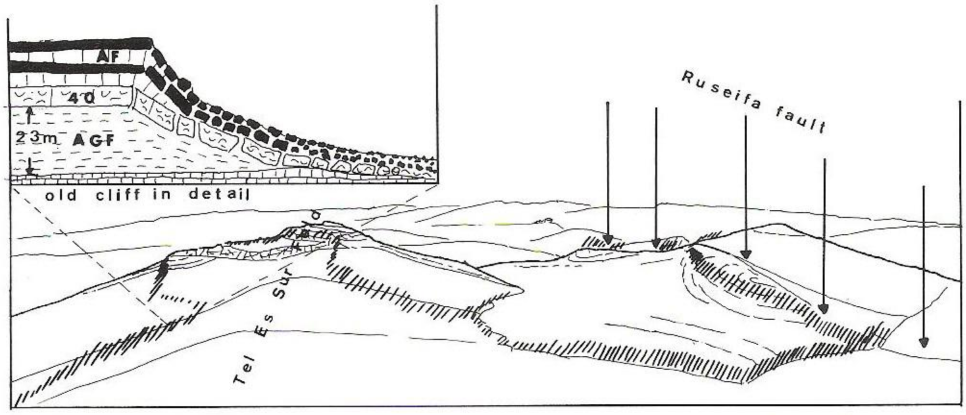


Fig. 13 View from Tel Es Sur (see fig. 5). Tel Es Sur fold lies in the north and Ruseifa Fault in the south (arrows). The former shore with its beach deposits is indicated by striation. At the citadel a cliff of the beach is exposed and sketched with chalks of the Ain Ghazal formation (AGF) washed out and hard beds of lower and upper Amman formation (40 and AF) fallen onto the plane of the former beach.

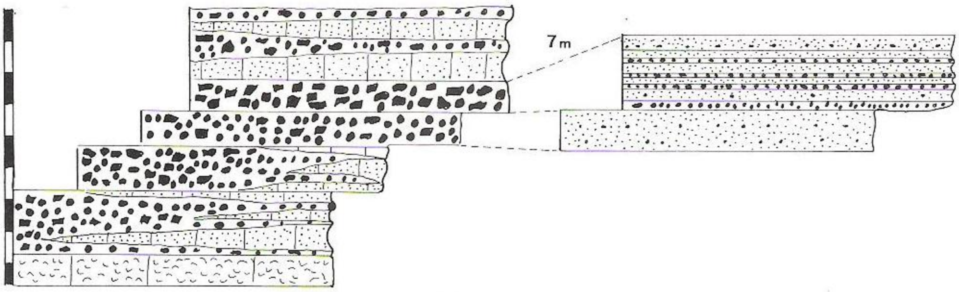


Fig. 14 Section B. Description see text. Each bar represents 1 m.

Amman Formation are eroded and reworked silicified oysters form part of the beach gravel. A little further to the west, limestone of the Wadi Sir Formation was eroded and beach gravel consists of edge-rounded limestone pebbles and blocks of up to 20 cm in diameter. The limestone itself shows small erosion cliffs still partly covered by beach pebbles, most of them with the same lithology as the cliff rocks. Erosion bench and beach deposits follow a small fault perpendicular to Ruseifa fault that displaced limestone beds of Wadi Sir Formation for a few metres. This fault was not revived later and is now partly covered by the beach gravel and sands of Ruseifa Formation.

The Ruseifa fault continues into the massive limestone at Tel Es Sur while beach deposits follow its base and change direction from westerly course to the north. The chalky marls of the Ain Ghazal Formation which here was originally 23 m thick have been washed out completely in a beach cliff so that the hard oyster-bed limestones of Member 40 of the Amman Formation broke down from the cliff forming beach gravel (Fig. 13).

At least 50 m of rock column were eroded between the beach deposits just shoreward of the oyster banks in section Z and the shore deposits of the Wadi Sir limestone cliff at the eastern flank of Tel Es Sur Island.

South of Ruseifa fault Amman Formation was eroded shedding its sands to the north into the area of Ruseifa phosphate mines. But here erosion did not reach Wadi Sir limestone as at Tel Es Sur Island.

H. Section on top of the fortification (Fig. 16, 17)

On the eastern continuation of the Tel Es Sur ridge an ancient fortification is found (Fig. 6, 13). On its southern slope synsedimentary folds of Amman Formation are truncated by beach beds of the Ruseifa Formation. On its eastern slope about 50 m

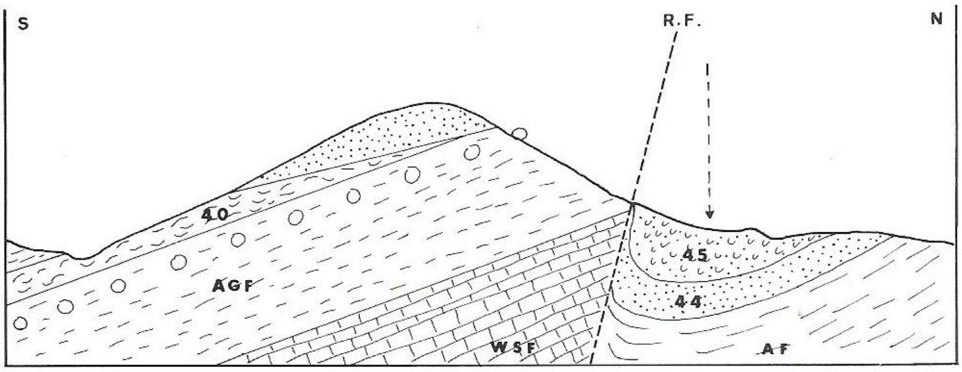


Fig. 15 Sketch of the geology just to the west of section Z shows Ruseifa Fault displacing Wadi Sir Formation (WSF) against Amman Formation (AF). Ruseifa Formation (member 44 and 45) disconformably overlie Ain Ghazahl Formation (AGF) and member 40 of Amman Formation (40) in the south and higher Amman Formation in the north.

from the walls of the citadel erosion unconformity is also exposed. On its western slope oyster limestone of the lower Amman Formation is truncated and overlain by phosphatic sand of Ruseifa Formation. Within the wadi to the south at (section V) about 25 m of chert and limestones overlying the oyster limestone (Member 41 and 42) of Amman Formation (1) are still preserved below base of Ruseifa Formation (4). A similar situation is found on the northern slopes, but here exposure is not good. The somewhat irregular truncation surface overlain by Ruseifa Formation reflects the course of Ruseifa fault and Tel Es Sur anticline.

The erosive surface at the platform of the citadel at its eastern end lies about 15 m below that of section M (Wadi Qattar) (Fig. 5) and is a few metres lower than on the west end of the platform. Chert beds above the erosive surface of the platform show clear indications of desiccation on intertidal mud flats. Fine-grained beds of Amman Formation below the truncation surface consisted of chert when they were eroded (1). Fine-grained beds above the truncation were lime mud (4). Beach conglomerates are reversely graded (8). Angular and subrounded chert pebbles and fragments of reworked Amman Formation form the small size gravel of the base while larger rounded mud balls of reworked beds of the Ruseifa Formation and oyster shells were deposited on top of this rock gravel (Fig. 19) because they were lighter at the time of their deposition. Later on, during diagenesis, mud balls were transformed into chert. Reversed grading regarding particle size is thus explained and actually consisted of normal grading regarding particle weight (Fig. 19). This original composition of beach deposits became disguised when mud balls were subsequently transformed into chert.

4. Depositional history

A. Amman Formation

Sea water of the shallow open sea was rich in dissolved mineral carbonate, phosphate and silica. This water came from the open Tethys ocean and probably was recharged in mineral content by upwelling currents that came from the depth of the ocean. When currents spread the cold water over the shallow broad shelf of the Arabian-Nubian continent with its warm climate it rapidly warmed up and a rich fauna and flora of planktonic and nectic organisms developed. Their skeletal hard parts as well as fecal pellets rained to the sea floor forming carbonate muds rich in organic matter. Productivity of the fertile water of the shelf was so high that organic deposits were not totally decomposed by rich benthic, soft bottom fauna comprising

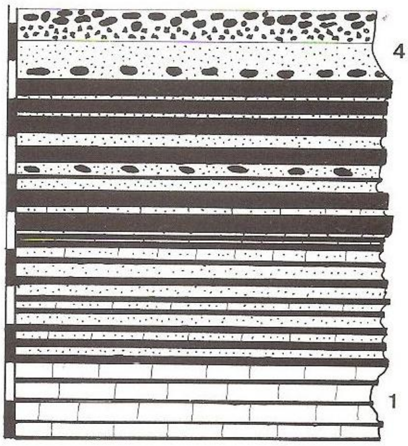


Fig. 16 Section V. Description see text. One bar represents 1 m.

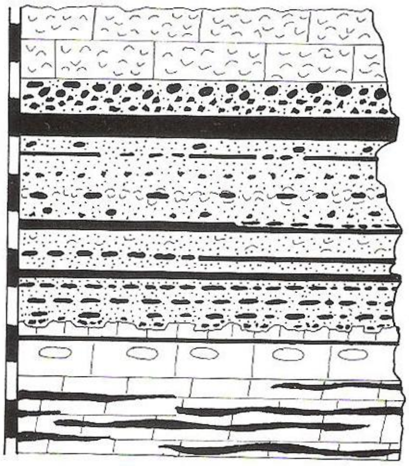


Fig. 17 Section C. Description see text. One bar represents 1 m.

among others molluscs and crustaceans. While the former left their shells in abundance, the late excavated their burrow systems now found in profusion.

From Upper Coniacian time onward through Campanian and Maastrichtian periods fecal pellets and larger organic and phosphatic skeletal hardparts were transferred into phosphatic particles after only shallow and short burial in the soft mud. This transition and early diagenesis occurred before sediment was indurated and before aragonitic shell became dissolved. Even minute and thin shells, larval gastropods and bivalves and just hatched ammonites (BANDEL, 1982) remained unchanged. Phosphatisation of fecal pellets occurred in the soft mud due to interstitial solutions rich in phosphate ions and fixation of these to the organic matter and mucus.

When periodic currents washed across the muddy bottom calcareous shells as well as phosphoritized pellets and skeletal particles were winnowed out and enriched in sands, now intercalated with the fine-grained beds. From the sand infaunal benthic organisms excavated their feeding or dwelling burrows, riddling the muddy beds below. These, therefore, commonly became biologically brecciated. In many beds this is due to U-shaped burrows with about 1 cm wide tunnels, a 3 cm distance between the tunnels and 10 cm tunnel length. U-burrows can be very close to each other and several generations of them may have been excavated from the mud bed in different orientations and inclinations. Tunnels are filled with phosphatic sand and the result was a mud bed consisting of irregular clasts surrounded by sand. Diagenesis later on transferred the mud into chert. Less than 10 cm thick beds in this way have been transformed into layers that look very similar to current-transported intraclast beds. Usually former mud beds, in addition, are riddled by *Ophiomorpha*-like tunnel systems. This tunnel network excavated by crustaceans often follows old bedding planes and several generations of burrow systems may also result in a brecciated appearrance of the chert bed.

Compacted and bored mud layers exposed to current-winnowing fell into irregular mud intraclasts. Redeposited intraclasts have retained their angular outline when transported for only a short way or have become rounded into mud pebbles when transported for longer distances. Redeposited clasts or pebbles commonly were again bored by the activity of tunnel excavating thalassinoid crabs in the sand. Mud balls or intraclasts often show traces of compaction of the beds from which they were eroded. In accordance with compactional features observed from many chert beds in place 1 : 1 to 5 : 1 volume shrinkage is present.

III. More deeply burried sediment here and there was compacted to up to 6 : 1 of its original volume as is easily reconstructed from formerly round burrow tunnels which have changed their shape in accordance to the decrease in volume. But only such tunnels can be used for interpretation that have not been filled by sand. Many beds, especially those composed of sand-sized particles or those with much carbonate, show little compaction. Aragonite dissolution began before compaction ended, but under deeper burial than phosphatisation. All molluscan shells that had been aragonitic dissolved. Small ones were only preserved when quartz took the place of the former shell, which occurred near silicifying former mud beds. Everywhere else they disappeared without a trace due to latest compaction by grain to grain shifting. In bigger shells the aragontic material was replaced by silica or calcite. Silica mainly derived from the skeletal opal of planktonic organisms and became enriched in the pore water when the tiny skeletons dissolved. Former sands were usually leached of silica which migrated into the fine-grained material. This movement of dissolved silica effected continuous beds in the same way as mud clasts or mud balls. Calcitic remains commonly survived all steps of diagenesis but in many cases were totally or partly silicified. Here and there calcareous concretions formed preserving different stages of diagenesis prior to silicification. In their interior the originally present shells have become preserved, recrystallized, but undeformed. A rich fauna was common throughout in marl, chalk, and sand, but in most instances has totally or partly disappeared during later diagenesis.

B. Ruseifa Formation

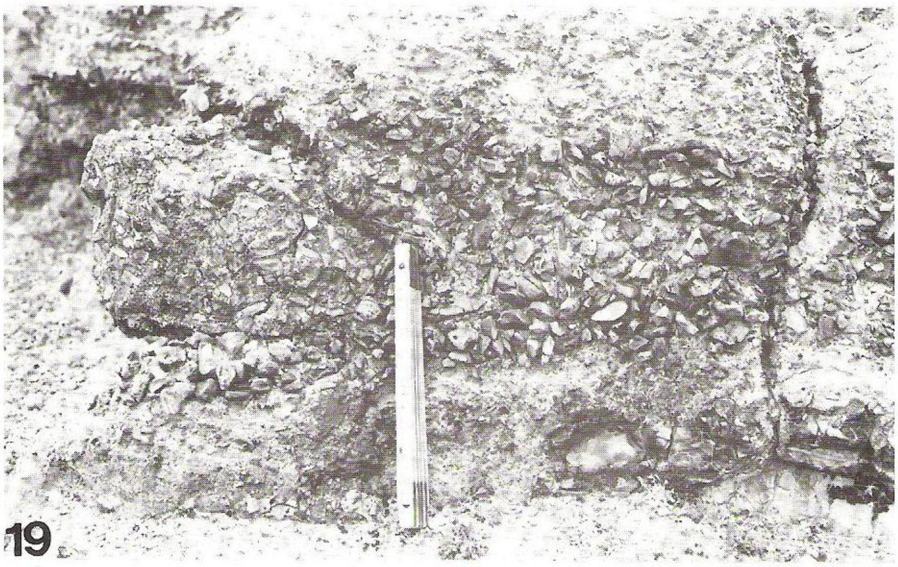
Intercalations of mud and phosphatic sand with a dominance on the side of the sand is characteristic for Ruseifa Formation. Sand was not only derived from winnowed muds but to a large extent from eroded beds of Amman Formation. Limestone concretions form Ruseifa have preserved the structure of muddy beds well. They can be totally undisturbed by bioturbation, can show single burrows and can totally be churned by bioturbation. This alternation of sediments with traces of much benthic marine life to no signs of marine life is also documented by the type and content of body fossils. In laminated muds of coastal lagoons with anoxic or salinal water near or in the bottom substrate fish skeletons remained connected. Bioturbated limestone beds, on the other side, may contain remains of a rich molluscan, crustacean and vertebrate fauna, characteristic of shelf sea.

Compacted, bioturbated or laminated muds are usually penetrated by crab burrows of *Ophiomorpha* type which had exit and entrance in sand layers and, therefore, have usually become filled with sand. Sometimes such burrow systems show tunnels which are still open and have never been filled by sediment or cement.

While at Ruseifa conditions of the shallow sea prevailed during the deposition of the studied beds of Ruseifa Formation, deposits at the same time formed on intertidal flats near the Tel Es Sur area. Muddy layers were baked by the sun so that vertical and horizontal shrinkage cracks formed. The mud itself is commonly finely laminated, often in a undulating stromatolitic manner as is formed when algal mats are present. Sands were settled by a fauna of crustaceans which excavated their burrows and worked sand into the muddy layers. Reworking of desiccated mud layers is common, and intraclasts, showing the characteristic upturned margins and flat shape, have been deposited overlapping each other like the tiles on a roof. Intraclasts were not only deposited on sand but also on mud.

Oysters in dense settlements grew near to the shore, probably in the lower intertidal area. Here periodic exposure to air kept away most of oyster-predators but could easily be tolerated by the oysters themselves as is shown by comparable oyster settlements of our time. The shore line closely follows structural features like Ruseifa fault and Tel Es Sur anticline. The eroded land was only that of an island or a chain of islands with sea to the north and to the south. Quartz sand did not reach the area, while at the shore to the continent in SE Jordan it is mixed with phosphatic sand (BENDER, 1968, 1975).


18


19

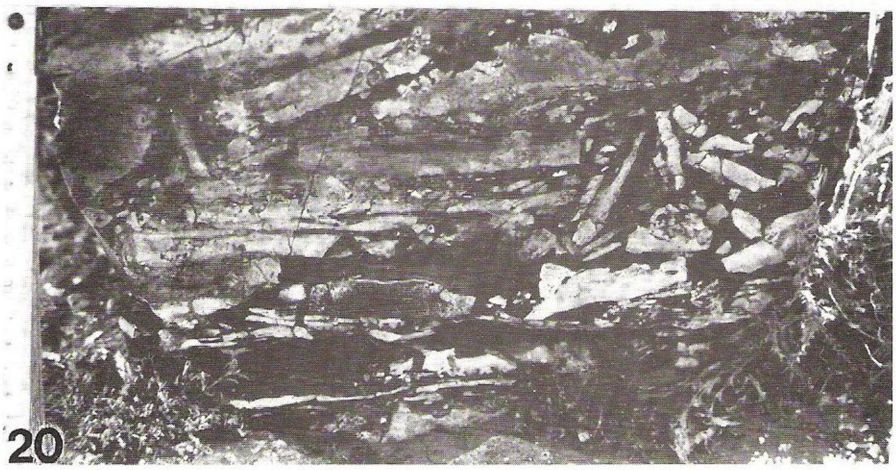

20

Fig. 18 The fold as it is exposed in Wadi Qattar. Section M was measured on its northern flank (right).
Fig. 19 Beach-gravel with reversed grading as it is exposed on the citadel.
Fig. 20 Chert bed showing characteristic intraclasts.

5. Discussion

Amman Formation occurs widespread in Jordan in its typical lithology and only in the southeast of the country it wedges out and is replaced by continental varicolored sandstone (BENDER, 1975). At time of deposition, mainly during Campanian, the shore lay in the far south of Jordan. Thickness of Amman Formation varies when different parts of Jordan are compared, and it is correlated with occurrence of phosphorite ores in the overlying beds of Ruseifa Formation. Near Amman and in Ruseifa the Amman Formation may have been totally eroded or measure up to 90 m; near Al Hasa, about 120 km to the south of Amman, Amman Formation may measure less than 20 m (BENDER, 1975); about the same distance to the NNW it is almost 40 m thick (MIKBEL & ABED, 1985). In these three occurrences Ruseifa Formation locally contains thick and exploitable beds of phosphorite ores (sand). Between Amman and Al Hasa, in the Wadi Mujib, in contrast, Amman Formation is approximately 135 m thick (BENDER, 1975), and Ruseifa Formation measures 90 m in thickness, much more than the 10 m in the NNW of Jordan, the about 25 m at Ruseifa, the 40 m at Al Hasa (BEERBAUM, 1977), and the about 12 m at Esh-Shidiya (KHALID & ABED, 1982) in the south of Jordan. In Wadi Mujib sedimentation continued from begin of Amman Formation to beyond the end of Ruseifa Formation without notable interruption, while in the north and the south of this area structural unrest resulted in the elevation of the sea floor to a level where it became eroded and sands winnowed from muds. In the area of Tel Es Sur sea bottom was raised above sea level so that a chain of islands formed from which sediments of the Amman Formation were eroded and redeposited to the north.

Structural unrest had already left its traces in the deposits of Amman Formation around Amman and to about the area of Qatrana in the south of it. Small scale fold-like synsedimentary structures with an amplitude of few meters and wave length of about 5–25 m do not affect the underlying and overlying beds (RUEF, 1967; own observations). Most diapiric folds and domes are found in the lower beds of Amman Formation that overlie the chalky Ain Ghazal Formation directly. South of Qatrana, where Ain Ghazal Formation is not developed, synsedimentary folds are absent or rare. Water released during the diagenesis of the marly chalks of the Ain Ghazal Formation pushed up the well bedded mud-sand intercalations of the deposits of the Amman Formation in diapiric mounds and structural unrest expressed in earth quakes may have triggered their formation. But also at later stages of deposition of the Amman and Ruseifa Formations diapiric folds formed, but of smaller size. RUEF (1967) thought that unrest connected to the Jordan Rift caused diapiric movements but it is more likely that they are connected with faults that follow the margins of the Arabian-Nubian Continent and cross the Rift lineament. Faults like Ruseifa Fault were later cut off and displaced by the Rift, probably not earlier than Mid Tertiary time (BANDEL, 1981).

Faults running roughly from NE to SW are connected to the phosphate beds also in other areas than that of Ruseifa. In the Al Hasa area BEERBAUM (1977) noted the co-occurrence of horst and graben structures and phosphate enrichment. SHILONI (1981) correlated uplift and erosion of Mishash Formatin (equivalent of the Amman Formation west of the Jordan Rift) with the redeposition and enrichment of phosphorite found in Beer Sheva valley. Movements during and after deposition of Mishash Formation were also described by FLEXER et. al. (1970) and GILAT & HONIGSTEIN (1981). In the Western Desert of Egypt GARRISON et. al. (1979) analysed phosphorite sand of Abu Tartur and noted that phosphatic grains had been winnowed from muddy substrate and concentrated into offshore tidal sand bars during an interval of sea level lowering. Phosphate ore of Abu Tartur has formed due to synsedimentary faulting in this part of Egypt during Campanian time due to which portions of the large shallow shelf of the Tethys ocean were raised above sea level (own observations).

6. Conclusions:

1.) Most phosphorite particles formed during early diagenesis within soft bottom substrates. In Jordan phosphorite fecal pellets began to form during the Upper Coniacian and from there on continuously into Maastrichtian time.

2.) Final compaction of the sediment, aragonite dissolution and chertization are steps of diagenesis after phosphatization was completed. Muddy sediments were later usually transformed into chert under a cover of at least 10 m of sediment.

3.) During deposition of the Amman Formation at Campanian time North and Central Jordan were covered by the shallow shelf sea. Highly productive upwelling water of the Tethys Ocean covered the shelf.

4.) With begin of Ruseifa Formation faults in their position roughly following the contour of the continental margin of the Arabian-Nubian landmass became active. The area between raised blocks, some of which forming island chains, remained submerged and the shore to the continent lay in the south of Jordan.

5.) From exposed and shallow sea bottoms phosphoritic sand sized particles were washed out and were concentrated in off-shore sand bars. In the Ruseifa area material was eroded along an island chain that accompanied Ruseifa Fault.

6.) Concentrations of phosphoritic sand along and near to zones of structural unrest is not a phenomenon found only in Jordan but is widespread in other areas of the shelf of the Arabian-Nubian Continent and the southern shores of the Tethys ocean at Campanian and Maastrichtian times. Similar deposits formed, for example, in Israel and Egypt.

References

ABED, A. M. (1982): Depositional environments of the early Cretaceous Kurnub (Hathira) sandstones, North Jordan. Sediment. Geol. 31: 267–279.

BANDEL, K. (1979): The depositional environment of amber bearing rocks in Jordan. Dirasat 6: 39–62.

BANDEL, K. (1981): New stratigraphical and structural evidence for lateral dislocation in the Jordan Rift Valley connected with a description of the Jurassic Rock Column in Jordan. N. Jb. Geol. Paläont. Abh. 161: 271–308.

BANDEL, K. (1982): Morphologie und Bildung der frühontogenetischen Gehäuse bei conchiferen Mollusken. Fazies 7: 1–198.

BANDEL, K. & J. F. GEYS (1985): Regular echinoids in the Upper Cretaceous of the Hashemite Kingdom of Jordan. Ann. Soc. Géol. Nord, CIV, 97–115, Mai 1985.

BANDEL, K. & J. WIEDMANN: Litho- and biostratigraphy of the Upper Cretaceous of North Jordan (Amman area). – In press.

BENDER, F. (1968): Geologie von Jordanien. 230 p. Stuttgart (Borntraeger).

BENDER, F. (1975): Geology of the Arabian Peninsula, Jordan. Geol. Surv. Prof. Paper. 560–I: I1–I36.

BEERBAUM, B. (1977): Die Genese der marin-sedimentären Phosphatlagerstätte von Al Hasa (westliches Zentraljordanien). Geol. Jb. Reihe D, 24, 58 p.

FLEXER, A., R. FREUND & Z. REISS (1970): Santonian paleostructure of the Galilee. Isr. J. Earth Sciences 19: 141–146.

FREUND, R. (1965): A model of the structural development of Israel and adjacent areas since Upper Cretaceous times. – Geol. Mag. 102: 189–205.

GARRISON, R. E., C. R. GLENN, P. D. SNAVELY & S. E. A. MANSOUR (1979): Sedimentology and origin of Upper Cretaceous phosphorite deposits at Abu Tartur, Western Desert, Egypt. Ann. Geol. Surv. Egypt 9: 261–281.

GILAT, A. & A. HONIGSTEIN (1981): The polyphase history of the Qana'im Valley fault zone. Geol.-Surv. Israel, Current Research 1981: 63–68.

HUFNAGEL, H. (1984): Die Ölschiefer Jordaniens. Geol. Jahrb. A75: 295–311.

KHALID, H. & A. M. ABED (1982): Petrography and geochemistry of Esh-Shidiya Phosphates. Dirasat 9: 81–102.

MIKBEL, S. & A. M. ABED (1985): Discovery of large phosphate deposits in North-West Jordan. Dirasat 12: 125–136.

MIKBEL, S. & W. ZACHER (1981): The Wadi Shueib sructure in Jordan. N. Jb. Geol. Paläont. Mh. 1981, 9: 571–576.

REISS, Z. (1962): Stratigraphy of phosphate deposits in Israel. Isr. Geol. Surv. Bull. 34: 1–23.

RUEF, M. (1967): Zur Stratigraphie und Tektonik der Kreide Jordaniens mit einem Beitrag zur Genese gefalteter Kieselgesteine. Unpubl. Diss. Ruprecht-Karl-Univ., Heidelberg.

SHILONI, Y. (1981): The national Phosphate survey project 1981 exploration stage. Geol. Surv. Israel, Current Research 1981: 63–68.

WIESEMANN, G. (1969): Zur Tektonik des Gebietes östlich des Grabenabschnittes Totes Meer–Jordantal. Beih. geol. Jb. 81: 215–247.