Early diagenesis of Late Cretaceous chalk-chert-phosphorite hardgrounds in Jordan: implications for sedimentation on a Coniacian-Campanian pelagic ramp

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ABSTRACT

Hardgrounds and omission surfaces are rare in the predominantly pelagic and hemi-pelagic chalk, chert and phosphorite lithofacies association that forms the Upper Cretaceous (Coniacian to Maastrichtian) Belqa Group succession in central Jordan. However, newly-described hardgrounds of regional extent at the base of the Dhiban Chalk Member (Campanian) in central and south Jordan reveal a complex history of sedimentation and early diagenesis. Following drowning of the Turonian carbonate platform during the Coniacian, the chalk-chert-phosphorite association was deposited on a pelagic ramp in fluctuating water depths. The Mujib Chalk and Dhiban Chalk members represent high-stand sea levels, separated by a regressive, low-stand chert-rich unit (Tafilah Member). Hardground successions can be traced over 100 km, and show an early diagenetic history of phosphatisation and biogenic silica lithification from opal-A to opal-CT and quartz that resulted in penecontemporaneous chert deformation, followed by submarine bioerosion and colonisation by corals and/or bivalves. Subsequent deposition of detrital, remanié phosphatic chalk passing up into pelagic coccolith-rich ooze reflects a transgressive third-order sea-level rise during the Early Campanian. These events provide a time-frame for early silica diagenesis and subsequent hardground development. Regional variations in the hardground successions and their early diagenesis are attributed to their precursor host sediment and relative palaeogeographic position on a homoclinal ramp at the southern margin of the Neo-Tethys Ocean.

INTRODUCTION

The Cretaceous to Eocene succession in Jordan and surrounding countries is characterised by passive continental margin depositional sequences, which pass vertically (and laterally) from alluvial/paralic to carbonate shelf and pelagic ramp settings (Flexer, 1971; Bender, 1974; Flexer et al., 1986; Powell, 1989; Lewy, 1990; Abed and Kraishan, 1991; Schulze et al., 2005; Powell and Moh'd, 2011). Hardgrounds and omission surfaces are rare in the Coniacian to Maastrichtian pelagic and hemi-pelagic, chalk-chert-phosphorite succession in the Levant region (Jordan and adjacent countries; Figure 1), compared to European Cretaceous chalk successions (Kennedy and Garrison, 1975; Bromley and Ekdale, 1987; Jarvis, 1980; 1992; Grant et al., 1999; Jarvis et al., 2001; Mortimore, 2011). This paucity is probably the result of more continuous sedimentation on the mid- to inner-ramp setting of the southern Neo-Tethys Ocean (Stampfli and Borel, 2002). Hardgrounds, similar to those described in this study, have been reported from the Turonian/Coniacian and Coniacian/Santonian boundaries in Kazakstan (Gruszczynski et al., 2002), suggesting that sea-level rise that triggered these events may have been more or less synchronous in a regional context throughout the Neo-Tethys Ocean. Rapid lateral and vertical variations in the lithofacies, and the absence of distinct marker beds, have hindered lithostratigraphical correlation of the Coniacian to Maastrichtian strata in the region (Flexer and Starinsky, 1970; Garfunkel, 1978; Soudry et al., 1985; Powell, 1989; Abed and Kraishan, 1991; Powell and Moh'd, 2011). However, the recognition of approximately synchronous hardgrounds of regional extent is supported by biostratigraphical data (Dilley and Azzam, 1985); these surfaces can be correlated for over 100 km, at approximately right angles to the palaeoslope.

In this paper, we describe the petrology, sedimentology and palaeogeography of a hardground of regional significance at the boundary between the Early Campanian Tafilah Member and the overlying Dhiban Chalk Member (Wadi Umm Ghudran Formation (Powell, 1989). The study provides new information on the nature and timing of sedimentation, diagenesis and penecontemporaneous folding in mixed silica, coccolith ooze and phosphorite precursor sediments, below and above the hardground surfaces. The latter were colonised by a variety of benthic fauna including colonial corals and oysters. The transition from opal-A to opal-CT, and finally to quartz during early diagenesis is based on experimental studies (Kestner et al., 1977; Mitsui and Tauchi, 1977), deep-sea drilling and outcrop studies (Behl and Garrison, 1994; Bohrmann et al., 1994), and seismic reflection data (Davies et al., 1999; Davies, 2005). This silica transition is accompanied by volume reduction phases, with the potential to generate penecontemporaneous early diagenetic deformation structures such as folds and troughs (Davies, 2005). Examples of hummocks and troughs in a polygonal plan-form have been described from Oligocence chert-rich sediments in the North Atlantic (Davies, 2005). Although the diagenetic deformation process in these Oligocene sediments is thought to have taken place during early burial diagenesis at depths of approximately 100 to 200 m, it does present a possible mechanism for the chert folds described from the localities in Jordan, albeit at shallower burial depths and earlier in the diagenetic process in these Late Cretaceous examples. The study helps our understanding of sedimentation and the timing of early diagenesis of siliceous and calcareous hemi-pelagic and pelagic sediments in a Late Cretaceous ramp setting (Powell and Moh'd, 2011).

Infra-regional correlation of hardground sequences along the palaeo-depositional strike provide important information on relative sea-level fluctuations on the southern margin of Neo-Tethys, which comprised part of the Arabian and Levant plates during a period of global sea-level rise in the Late Cretaceous (Haq et al., 1988; Stampfli and Borel, 2002; Haq and Al-Qahtani, 2005; Sharland et al., 2001; 2004).

METHODOLOLGY

This study is based on detailed logging of 17 key sections through the Late Cretaceous succession in central and southern Jordan, carried out to determine the broad stratigraphical, palaeogeographical and sedimentological framework (for details see Moh'd, 1986; Powell, 1988; Moh'd, 1992; Powell, 1989; Powell and Moh'd, 2011). A number of these sections were sampled in detail at a vertical interval of 0.10 m to determine the nature of the lithostratigraphical boundaries, with a focus on the hardground sections at Wadi Mujib and Jibal Khureij (Figures 1 and 3). The hardground at the base of the Dhiban Chalk Member (Figure 3; see also Powell and Moh'd, 2011, their figure 6) has been traced in wadi sections over 100 km along strike, at approximately right angles to the palaeoslope (Powell, 1988; 1989; Powell and Moh'd, 2011). In this paper, we describe two localities that were sampled in detail: (a) Wadi Mujib, in central Jordan and (b) Jibal Khureij, in the southern Wadi Araba (within the Dead Sea Rift Valley) (Figures 1 and 3). The Wadi Mujib section has recently been partly removed by road widening, but it was exposed in a roadside cutting (31°28′28′′N, 35°47′06′′E) adjacent to the King's Highway, at a distance of about 1 km from the tourist viewpoint, on the northern flank of Wadi Mujib. At Jibal Khureij (30°11′04′′N, 35°11′02′′E), in the central-south Wadi Araba, the hardground and overlying chalk occupy the same stratigraphical position (Figure 3), but the section has been displaced about 110 km to the south as a result of left-lateral shear on the Dead Sea Rift fault (Figure 1) (Freund et al., 1970; Powell et al., 1988).

Thin sections, polished thin sections were prepared and samples analysed using both standard scanning electron microscope (SEM) and backscattered SEM (BSEM) techniques. BSEM on polished thin sections was used to reveal mineralogical variations and textures not visible using transmitted light microscopy, especially in anisotropic minerals such as phosphate. Seven samples of the carbonates immediately below and above the Wadi Mujib hardground were analysed by electron microprobe to determine their Ca:Mg:Fe ratio indicating the presence of non-ferroan- or ferroan-dolomite. The Ca:Mg:P ratio was analysed to determine proportion of francolite (carbonate apatite) of the phosphatised grains.

STRATIGRAPHICAL AND SEDIMENTOLOGICAL SETTING

Across the mid- to inner-ramp of central Jordan hardgrounds, sub-marine erosion and omission surfaces occur in the Campanian Wadi Umm Ghudran Formation (Belqa Group) (Parker, 1970; Powell, 1989; Powell and Moh'd, 2011) (Figure 2). In central Jordan, this formation (Figures 2 and 3) is a predominantly chalky unit subdivided into three members, in ascending order: the Mujib Chalk, Tafilah and Dhiban Chalk. The three-fold division can be traced throughout central Jordan, where the members form distinctive mappable units in the lower part of the Belqa Group (Quennell, 1951; Parker 1970; Powell, 1988; Moh'd, 1992). However, the chalk members wedge out to the south and east of Tafilah (Figures 1 and 3), where they are replaced by coeval, lithologically heterogeneous strata consisting of chert, phosphatic chert, dolomite and marl, typical of the Tafilah Member (Powell and Moh'd, 2011, their figure 6). The tripartite sequence is interpreted as reflecting relatively deeper (chalk) and shallower (heterogeneous facies) water-depths in a pelagic, mid- to inner-ramp environment (Figures 1 and 3). To the southeast, the Tafilah Member passes laterally to marine shoreface siliciclastic sandstone (Figure 1). Lithostratigraphical correlation with areas west of the Dead Sea Rift (DSR) is shown in Figure 2; the Mujib Chalk and Dhiban Chalk units are equivalent to the Lower (1^{st}) Chalk and Upper (2^{nd}) Chalk, respectively, of the Menuha Formation in the Negev (Steinitz, 1977; Flexer and Honigstein, 1984; Reiss et al., 1985).

Sedimentation of the Upper Cretaceous (Coniacian to Eocene) Belqa Group in Jordan and adjacent countries comprises a genetic depositional mega-sequence deposited in a hemi-pelagic/pelagic carbonate ramp setting (Powell and Moh'd, 2011) in response to varying water depths and marine onlap/offlap (Figure 1). Subtle variations in slope geometry on the carbonate ramp (Burchette and Wright, 1992) are reflected in gradational depositional environments (Sass and Bein, 1982; Flexer et al., 1986; Powell, 1989; Schulze et al., 2005; Powell and Moh'd, 2011, their figure 29). These pass from deeper-water chalk and marl lithofacies associations in the northwest, to hemi-pelagic mid- to inner-ramp associations in central Jordan, and to increasingly shallow-marine dolomite or marine siliciclastic associations in south and east Jordan (Figure 1). Incipient folding during the Coniacian to Maastrichtian, associated with the development of the Syrian arc (Chaimov et al., 1992) is well developed west of the rift within the Levant (Palestine-Sinai) sub-plate (Cohen et al, 1990), but the area to the east (Arabian Plate) was not subjected to such intense, intra-plate compressional folding. Consequently, growth folds, which affected sedimentation in the Negev area during the Campanian to Maastrichtian (Cohen et al., 1990), are not apparent on the mid- to inner-ramp setting (central Jordan), with the result that Coniacian to Maastrichtian facies belts and sequences (Belqa Group) can be traced over a wide area on this relatively stable part of the ramp. However, in the Amman area (north Jordan) compressive folds are thought to have been locally initiated during the Santonian to Campanian (Mikbel and Zacher, 1986), resulting in the deposition of shallower-water chert succession that is coeval with deeper-water chalks, typical of the stable ramp located to the south, in central Jordan.

A regional rise in sea-level (second-order) and marine transgression during the Coniacian (Type 2 sequence boundary of Sarg, 1988) resulted in drowning of the Cenomanian to Turonian rimmed carbonate-shelf by Late Coniacian times (Powell, 1989; Schulze et al., 2003; Powell and Moh'd, 2011). Sedimentation during Coniacian to Early Campanian time was characterised by a tripartite, chalk-chert-phosphorite lithofacies association, deposited in shallow to moderate water depths (ca. 30-100 m) in a ramp setting. The marked change in sedimentation from rimmed carbonate shelf to hemi-pelagic/pelagic ramp is attributed to Neo-Tethyan mid-oceanic rifting, tilting, intra-cratonic deformation and subsidence of the platform (Sass and Bein, 1982; Robertson and Dixon, 1984; Flexer et al., 1986; Powell and Moh'd, 2011). These events were associated with changes in oceanic biogenic productivity and upwelling currents on the southern margin of Neo-Tethys, which in turn, resulted in hemi-pelagic and pelagic sedimentation (Almogi-Labin et al., 1993; Kolodny and Garrison, 1994).

Oceanic upwelling and high organic productivity resulted in the deposition of calcareous ooze (chalk), siliceous ooze (chert, porcellanite), marl and phosphate, the latter reaching ore-grade during the Maastrichtian (Flexer, 1968, 1971; Reeves and Saadi, 1971; Bartov et al., 1972; Bender, 1974; Moh'd, 1986; Flexer et al. 1986; Flexer and Honigstein, 1984; Soudry et al., 1985; Powell, 1988, Powell, 1989; Abu Ajamieh et al., 1988; Abed and Kraishan, 1991; Kolodny and Garrison, 1994; Pufahl et al., 2003).

The pelagic outer-ramp lithofacies association consists of chalk (composed predominantly of calcareous nanoplankton, diatoms and planktonic foraminifera), locally with up to 50% detrital phosphatic skeletal fragments (francolite-dahlite), including fish teeth and bivalve fragments at the base (Magaritz, 1974; Powell, 1989; Abed and Kraishan, 1991). In contrast, the hemi-pelagic mid- to inner-ramp association consists of laterally-impersistent intercalations of chalk, porcellanite, chalky marl, chert and phosphorite. Porcellanite is usually pink, white or buff in colour, and is composed of siliceous microfossils including silicoflagellates (Moshkovitz et al., 1983).

HARDGROUND SEQUENCES

Wadi Mujib

The sequence is shown in Figures 3 and 4. The marked change in lithology at the base of the Belqa Group is represented by the disconformable junction between a lower chalk unit (Mujib Chalk Member) and the underlying shelly wacke-packstones of the underlying platform carbonates (Ajlun Group). The basal part of the Mujib Chalk Member (Figures 3 and 4) contains abundant detrital clasts (phosphate; fish and marine reptile teeth and bone fragments), representing a condensed sequence following a depositional hiatus as the rimmed shelf (Ajlun Group) was flooded during a rapid sea-level rise during the early Coniacian (Powell and Moh'd, 2011).

The overlying Tafilah Member comprises, in upward sequence, laterally-wedging oyster-coquina dolomite, nodular chert with carbonate concretions, phosphatic chalky marl (laminated carbonate), phosphatic dolomite, and thin-bedded or banded grey-white chert and porcellanite; the latter passes both laterally and vertically into soft, white 'tripoli' a soft, porous microcrystalline silica deposit used as an abrasive (Abu Ajamieh et al., 1988). Low-amplitude, disharmonic folds at the top of this unit are truncated by a hardground surface (Figure 4c and d); folding predates deposition of the upper (Dhiban) chalk. The hardground surface (chert and chalky marl) is slightly irregular, with a maximum palaeo-topographical relief up to 0.10 m. It is locally bored (*Lithophaga*) and encrusted by smooth-shelled oysters. The hardground surface was also locally colonised by monospecific, fasiculate growths of the colonial scleractinian octocoral *Oculina* sp., which forms small patch reefs, up to 1.5 m in diameter (Figures 4d and 5), and which, in turn, were bored prior to deposition of the overlying detrital, phosphatic chalk (Dhiban Chalk Member). Above the basal detrital phosphatic chalk (ca. 0.10 m thick), the chalk is thick-bedded and white in colour, with small (1-2 mm) brown limonitic flecks, probably the remains of pyrite-lined burrow-fills. Small-diameter (0.02 m) *Thalassinoides* burrows, backfilled with coarser grained detrital phosphatic chalk, are visible on weathered bedding planes, along with clusters of small oysters.

Jibal Khureij and Edh Dhira

The succession, described above from Wadi Mujib, is typical of central Jordan. Regionally, the chalk members thicken towards the west and, conversely, become thinner and less distinctive (by way of passage increasingly into chert, phosphatic dolomite and marine siliciclastics lithologies, cf. Tafilah Member) when traced east and southeast towards the Late Cretaceous (Conaician to Maastrichtian) palaeoshoreline (Figures 1 and 3) (Bender, 1974; Powell, 1989). However, at Jibal Khureij in the central-south Wadi Araba (DSR), the hardground and overlying chalk occupy the same stratigraphical position (Figure 3), even though the expected lithofacies for this part of the Belqa Group, located about 175 km to the south of Wadi Mujib, would be the shallower-water association comprising chert, phosphatic dolomite and marine siliciclastics, which are, indeed, developed in the nearby Gharandal area (Powell et al., 1988). The presence of thick (relatively deeper-water) chalk units at Jibal Khureij can be explained by left-lateral shear along the Dead Sea – Gulf of Aqaba Fault, which displaces the Jibal Khureij outcrop (part of the Palestine – Sinai (Levant) Plate), about 100-110 km to the south, relative to the Arabian Plate (Quennell, 1958; Freud et al., 1970; Powell et al., 1988). The relative left-lateral shift of the depositional lithofacies by about 100 km is confirmed by the occurrence of a similar Jibal Khureij-like succession at the base of the Dhiban Chalk Member in the Edh Dira Basin (Figure 1), where bored concretions partially entombed in chalky marl are present (Figure 4e), offset to the north by about 100 km from Jibal Khureij.

The sequence at Jibal Khureij is very similar to that described by Lifshitz et al. (1985) from the southern Wadi Araba, although these authors do not record a hardground at the base of the upper (Dhiban) chalk. The Jibal Khureij sequence is similar to that of Wadi Mujib (Figure 3) but at this southern locality (and at Edh Dhira), the topmost beds of the middle Tafilah Member comprise large (up to 1.5 m diameter) microcrystalline limestone concretions embedded in soft chalky marl. Exposed bedding planes reveal hundreds of concretions at this locality (Figure 4e). In the topmost horizon, only the upper surfaces of the concentrations are crowded with endolithic, cup-shaped bivalve borings (Figure 4e and f), attributed to *Lithophaga* sp. The borings are infilled with detrital phosphate, fish and bivalve fragments with a matrix of dolomitic chalk (Figure 4e and f). *Lithophaga* shells are occasionally present *in situ* within the borings. The upper surface of the topmost, bored concretions appears to have been subjected to both bioerosion and chemical corrosion (dissolution), shown by the cross-sectional shape of these concretions, which exhibit a flatter upper surface (Figure 4e), compared to non-exhumed concretions lower in the succession. Although borings are mostly concentrated on the upper surface, some bivalves penetrated the exhumed sides of the concretions; boring is always absent from the undersides of the concretions (Figure 4e and f). Boring or burrow structures have not been observed in the marly chalk surrounding the topmost concretions, indicating a preference by *Lithophaga* for the early diagenetic firm substrates provided by the exhumed concretions. The upper surface of the bored hardground was colonised by clusters of the the gryphaeid oyster *Pycnodonte vesiculare (Lamarck)* during depositional hiatus (Figure 7), which, locally form a biostrome, up to 1 m thick. Detrital marly chalk (0.2-0.3 m thick) above the oyster biostrome contains rounded phosphate granules and fish fragments (teeth and bone), similar to the succession at Wadi Mujib. The succeeding, uniform, white, or locally pink, chalk contains few detrital fragments, but small clusters of gryphaeid oysters are present at some horizons.

Petrology of the Wadi Mujib hardground succession

Coniacian to Campanian chert in the region is considered to be biogenic in origin (Kolodny, 1969; Kolodny et al., 1980; Moshkovitz et al., 1983) comprising diatoms, silicoflagellates, sponge spicules, and radiolaria, although much of the original sediment was either a mixed calcareous/siliceous ooze, locally with bivalve shell (calcite) and fish or marine reptile bone (phosphorite) intraclasts (Figure 6a and b). Silicification occurred during early diagenesis as described below (Figures 6 and 7) *[what is the evidence for this - need to provided additional information on this; early diagenetric features are shown in Figures 6 & new Figure 7* *and outlined below]* and proceeded through various stages to produce the distinctive chert textures, including early diagenetic breccias *[what is the evidence for this - need to provided additional information on this]* (Kolodny, 1969; Steinitz, 1981; Fink and Reches, 1983; Powell and Moh'd, 2011, their figure 20). [evidence is from published literature and especially penecontemporaneuos micofaulted chert breccias shown in fig 20 of Powell and Moh'd, 2011]. It is not certain, however, whether fine lamination in the chert was due to primary variation in the concentration of siliceous microfossils in the sediment or to very early silicification of carbonate sediment at the sediment-water interface.

The beds below the hardground (Tafilah Member) consist of thin-bedded (0.05 to 0.10 m thick) laminated chert (locally altered to 'tripoli') with, in places, siliceous nodules and chalky partings (Figure 4b and c). Tripoli silica is a porous, weakly-indurated rock composed of microscopic quartz, with scattered dolomite crystals and sporadic phosphatic material (Figure 6a and 7d). Silicified coccolith plates showing varying states of preservation (Figures 6a and 6b) indicate that the origin of the tripoli was by replacement of a precursor lime-mud or mixed silica-chalk ooze by mobile silica.

Thin chert, locally interbedded with the chalk, consists of micro-quartz and crypto-quartz with chalcedonic quartz infilling fractures. SEM studies reveal that it is composed of euhedral, bi-pyramidal micro-quartz with sparse silicified foraminiferal and coccolith ghosts (Figure 6b), suggesting silicification of a mixed carbonate/siliceous sediment originally composed of siliceous microfossils such as diatoms, silicoflagellates, sponge spicules and radiolaria (Kolodny, 1969; Moshkovitz et al., 1983).

SEM anlaysis of the tripoli at this locality consists of poorly crystalline patches of silicified carbonate, in places the 'ghost' outline of large coccolith plates, with clusters of authigenic silica crystals, which have grown on coccolith plates (Figures 6b). The replaced carbonate has a 'speckly' appearance under backscattered electron microscopy (BSEM), whereas the authigenic crystals have a uniform, slightly paler grey colour and can clearly be seen to have grown freely into the numerous large pore spaces. The quartz crystals, up to 10 µm, are typically subhedral to euhedral with well developed rhombohedral faces, or occasionally present as simple hexagonal bipyramids.

Scattered non-ferroan dolomite rhombs, up to 400 µm in maximum dimension (new Figure 7d) occur within the bedded chert and in megaquartz-filled fractures, particularly below the hardground. The dolomite is non-stoichiometric, with excess calcium (between 54.3 to 58.7 mole % $CaCO_3$) and a mean composite of FeO (0.004), CaO (0.577), MgO (0.439) CO_3 (from seven microprobe analyses). The rhombs show a simple pattern of zoning under cathodoluminescence, generally with a non-luminescent core, and a red-luminescent outer rim, but in rare cases, a red-luminescent central zone is present (Figure 7e). *[Thin-section photomicrographs, including TL, CL and SEM,* *are necessary here to illustrate the features of dolomite and quartz: OK See new Figure 7]*

The laminated microfossil ooze contains both shell and bone fragments aligned along the bedding. Bivalve shells have mostly been wholly silicified. Replacive silica crudely preserves the original prismatic, lamellar or two layer structure of the precursor shells (new Figure 7a and b). The generally fine-grained nature of the silica in the chert-rich beds suggests that replacement was quite rapid and/or that concentrations of silica in porewaters were relatively high. High resolution BSEM show that silicification generally proceeded by preferential replacement of the carbonate along the growth lines of the shell, but in some areas by amalgamation of small (<20 μm diameter) spherical clusters of silica developed haphazardly across the shell (new Figure 7a and b). Chalcedonic rosettes, comparable to those described by Carson (1987) are also occasionally seen cutting across the original fabric of the shell. Some bivalves are preserved as alternating layers of silica and phosphate. Most bone fragments (apatite) are unaffected by silicification, although many phosphatic grains show a peripheral coating of chalcedonic quartz or microquartz (new Figure 7e).

Phosphate bone fragments (Figure 6e) within the chert have undergone variable stages of boring by endolithic algae and phosphatisation (Soudry and Champetier, 1983). In some examples, only the upper surface of the bone fragment is penetrated by endolithic tunnel borings indicating an early diagenetic process on the seafloor prior to burial (Figure 6e). Tunnel bores are often infilled with microscopic phosphatised peloids, a process of early phosphomicritization which was more prevalent in the formation of ore-grade phosphorite in the Al Hisa Phosphorite Formation, higher in the Senonian succession (Soudry and Champetier, 1983; Powell, 1989; Abed and Kraishan, 1991; Abed et al., 2007)

The detrital chalk, 0.3 m thick, overlying the omission surface is comprises chalk wackestone rich in detrital fragments, including phosphatic granules, apatite bone fragments, shark teeth, oysters and coral, with occasional small, sub-angular chert fragments (Figure 6c). Encrusting oyster shells are mostly composed of an irregular mosaic of non-ferroan and non-luminescent spar calcite, but a few shell fragments survive unaltered and retain their lamellar texture. Other shells are partly to wholly phosphatised. Voids left after the dissolution of former shells (probably aragonitic) are filled by two generations of calcite cement (Figure 7e); the first and earliest is non-luminescent and preserves the scalenohedral or blocky crystal forms of the initial cement phase; the second shows a moderately bright, orange-yellow luminescence, which is faintly zoned and tends to fully occlude the remaining void space. The second generation of calcite may be vein-fed because orange-yellow-luminescent cement also occurs as a fill of hairline fractures transecting the rock. *[cathodoluminescence photomicrographs would be useful to illustrate some of these feature; OK see Figure 7].*

A large proportion of the coarse-grained phosphatised grains are recognisable as skeletal remains (fish and reptiles) which, together with phosphomicritised oyster fragments and peloids, indicate that the water column supported a rich, prolific nektonic fauna that was preserved in low Eh/Ph bottom conditions.

Numerous bone and teeth fragments within the detrital chalk appear in thin section, under transmitted light, as colourless and pale yellow to darker yellow-brown phosphatic particles. These often show a layered internal structure similar to that of some molluscs or brachiopods, but some fragments exhibit more distinctive porous microstructures. The bone debris is commonly fractured. The bone fragments have a CaO/P_2O_5 ratio of between 1.52 and 1.61 and are relatively rich in P_2O_5, which is in excess of 32%. These data compare well with phosphates previously analysed from Jordan (Reeves and Saadi, 1971). Microborings in a minority of phosphatic grains within the basal chalk indicate colonisation by endolithic algae (Figures 6e and 6f). The borings are simple meandering tunnels usually without branches, and are often restricted to one surface of the particle, again indicating an early penecontemporaneous diagenetic process on the upper surface of the shell at the sediment-water interface, and prior to burial by detrital or pelagic chalk. Similar microborings are most common in present-day marine environments at shallow depths of less than 20 m (Swinchatt, 1969). Molenaar and Zulstra (1997) described similar coarse-grained remanié deposits above Coniacian-Maastrichtian chalk hardgrounds associated with early diagenetic nodular chert, although in their examples the encrusting organisms are bryozoa and serpulids.

The detrital chalk is overlain by uniform, soft white chalk composed of euhedral blocky calcite crystals (up to 5 µm in maximum dimension), coccolith plates and occasional well-preserved coccoliths, arranged randomly in a loose porous fabric (Figure 6d). Partial lithification of the chalk may have occurred under meteoric pore-water conditions as indicated by isotopic studies on broadly equivalent chalks exposed west of the Dead Sea Rift (Magaritz, 1974).

DISCUSSION

The timing of early diagenesis in these mixed chert-chalk-phosphorite successions deposited on the southern marginal ramp of Neo-Tethys is poorly understood. However, the sedimentation patterns and early diagenesis in these hemi-pelagic and pelagic sediments is revealed by detailed studies of the bedding surfaces and petrology of these sequences at critical sequence boundaries. In this section we discuss the depositional and diagenetic history of the Wadi Mujib and Jibal Khureij hardground successions; these are summarised diagrammatically in Figure 8.

Wadi Mujib

During the shallow-water regressive phase represented by the Tafilah Member chert-marl-phosphorite sediments, very early phosphatisation took place through endolithic boring of calcite shell and apatite bone fragments in relatively anoxic and reducing conditions on the seafloor (Figure 6c). Phosphatisation of the bone (francolite) and shell (carbonate) took place by a process of endolithic boring and cyanobacterial alteration (Soudry and Champetier, 1983) in an anoxic (reducing) environment at, or above, the sediment-water interface. The low diversity of foraminifera, diatoms and ostracods (Moshkovitz et al, 1983; Lifshitz et al, 1985) indicates a restricted environment. Phosphatisation is considered to have resulted from high organic productivity in the Neo-Tethys Ocean (Flexer and Honigstein, 1984; Soudry et al., 1985). Initial concentration of phytoplankton may have been due to oceanic upwelling of nutrient-rich water from deeper parts of the ocean, with further concentration, by winnowing, on the inner-ramp (Figure 8; Powell and Moh'd, 2011). Early diagenetic silicification of mixed biogenic siliceous and calcareous oozes, took place just below the sediment-water interface involving migration of silica and carbonate ions (Figure 6a and b). This was accompanied by volume changes (opal-A to opal-CT) in the silica sols in semi-lithified sediment, soon after deposition (early burial diagenesis).

Instability on the hemi-pelagic ramp, was probably triggered by these silica/carbonate sediment volume changes that resulted in gentle disharmonic folding of the chert-dominated beds (Figure 4b and c) and gravity slump folding, down the palaeoslope. Folding appears to have taken place whilst these sediments were semi-lithified.

Erosion of the semi-lithified and deformed chert/chalk beds occurred on the seafloor during a depositional hiatus, prior to endolithic boring by bivalves and subsequent colonisation of the firmground/hardground substrate by colonial octocorals on the undulating eroded and corroded edges of the chert/marl-rich beds (Figures 4c and 4d). There is no evidence of sub-aerial erosion, such as karst or pedogenic processes. We interpret the processes of deformation of the chert/chalk beds, subsequent sub-marine erosion, cementation, endolithic boring and encrustation as having occurred over short time interval within a submarine environment. Colonisation of the hardground by scleractinian octocoral colonies may indicate deposition within the photic zone, probably 10-40 m depth if these corals are hermatypic, i.e. include photosynthetic zooxanthellae algae in their soft tissue. However, *Oculina* sp. may be an ahermatypic deeper-water species not dependant on zooxanthellae for its metabolism and thus capable of growth in depths of 100 m or more.

Wispy laminated fabrics, and the presence of phosphatic peloids and granules, fish, teeth and bone fragments in the succeeding basal detrital chalk suggests deposition as a winnowed remanié deposit deposited during a rapid sea-level rise.

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As these localities are situated in slightly deeper-water, down the palaeoslope, the depositional and diagenetic history (Figure 7) reflects different precursor sediments as compared to Wadi Mujib.

Early migration of carbonate ions in the marly chalk ooze to concretion centres resulted in the early diagenetic development of microcrystalline carbonate concretions in slightly reducing conditions, a few centimetres below the sediment-water interface. There is no evidence of penecontemporaneous deformation of chert beds at this locality; this is a result of a relatively lower proportion of biogenic chert (present as silica sols) in the precursor sediments, further offshore.

Carbonate concretions were fully lithified prior to submarine winnowing and erosion of the entombing soft, marly chalk, thereby exposing the upper surfaces of the earlier formed carbonate concretions on the seafloor. Submarine corrosion and dissolution of the upper surfaces of the exposed concretions took place at the seafloor, resulting in asymmetric (flattened tops) cross-sectional profiles. The concretions provided a suitable hard substrate (hardground) for boring endolithic bivalves. Subsequently, during this depositional hiatus, the seafloor was colonised by encrusting oysters. Similarly, a phase of bioerosion and, in this case, colonisation by gryphaeid oysters (rather than colonial octocorals) took place during a phase of low sedimentation rate.

Deposition of pelagic foraminifera-rich cocolithophoroid ooze at the base of the Dhiban Chalk at all localities, marks a rapid sea-level rise following the depositional hiatus.

Silica Diagenesis

The contrasting sequences below the hardground at these two localities are typical of the downslope lithofacies variations in the upper part of the Tafilah Member. Many of the features now seen in these sediments, such as the replacive chert-tripoli, phosphomicritisation, and the formation of carbonate concretions are interpreted as resulting from early diagenesis of an original siliceous/carbonate ooze. Petrographical study of the chert in the Wadi Mujib section (Figure 6) indicates that the precursor sediment was probably fine-grained calcareous/siliceous ooze in which the carbonate was subsequently replaced by silica during early diagenesis. Silica was probably derived from the early diagenetic dissolution of metastable opal-A, present as diatoms and other siliceous microfossils (c.f. Moshkovitz et al., 1983), either within the topmost (10 – 15 cm) levels of the sediment pile, or at the sediment/water interface (Calvert, 1974). The pathways and the products of the dissolution and recrystallization of biogenic opal have been established from study of Cenozoic sediment cores recovered from various depths on the seafloor by the Deep Sea Drilling Project (Calvert, 1974; Bohrmann et al., 1994) and the North Atlantic (Davies, 2005). Biogenic opal dissolves in sediments and, under the right conditions, opal-CT crystallises from pore-waters before it, in turn, dissolves and is re-precipitated as microquartz. However, experimental studies (Berner, 1971) suggest the development of an intermediate stage where a gelatinous precipitate or silica gel forms before opal-CT. This is substantiated by the presence of brecciated laminated chert fabrics in both the Tafilah Member and the stratigraphically higher, chert-rich Amman Silicified Limestone (Powell and Moh'd, 2011; their figure 20).

Silicification commenced within the silica/carbonate ooze, following endolithic boring of bone and bivalve fragments and their cyanobacterial alteration to phosphate on the seafloor. Where silica has replaced the original prismatic layer structure of precursor bivalve shells, precipitation of silica must have commenced at about the same rate as carbonate dissolution, with near pristine preservation made possible only by a chemical diffusion process (Schmitt and Boyd, 1981; Holdaway and Clayton, 1982). The transition of biogenic silica from opal-A to opal-CT and subsequently to cryptocrystalline quartz is known to produce volumetric changes in semi-lithified silica-carbonate sediments (Kastner et al., 1977; Isaacs, 1982; Murray et al., 1992; Behl and Garrison, 1994) including deformation structures (Eichhubl et al., 1998; Davies et al., 1999; Davies, 2005). This is considered to be the driving mechanism for brecciated fabrics in individual laminated chert beds and disharmonic folds in chert-rich sequences (Powell and Moh'd, 2011, their figures 19 and 20) seen at Wadi Mujib. Faster rates of opal-A to opal-CT transition have been observed in pure silica ooze layers as compared to those with a higher proportion of clay, and other detrital minerals (Bohrmann et al. 1994) in Miocence sediments. This suggests that the opal transition, volume changes and density inversion took place preferentially in slica-rich precursor sediments compared to beds with a higher carbonate and phosphate content resulting in lateral displacement and folding of the chert beds. Fracturing of chert sols and the development of gentle folding of the semi-lithified chert beds is interpreted as the result of volume changes during early diagenesis. Chert layers were also deformed into asymmetrical, disharmonic folds up to 1 m in amplitude; these large-scale structures do not affect the chalk members above and below the chert-dominated horizons (Figure 4) supporting the hypothesis of diagenetic volumetric density changes during early and late lithification of siliceous oozes (chert sols) as a triggering mechanism, possibly enhanced by gravitational downslope slumping. The presence, at Wadi Mujib, of a regionally correlative hardground, above, and truncating, the folded chert beds constrains the timing of deformation (i.e. Early Campanian or pre-Dhiban Chalk, in this case). Furthermore, the absence of deformation structures in coeval non-siliceous sediments at Jubal Khureij suggests that deformation is indeed intimately related to aspects of early silica/carbonate diagenesis in mixed oozes. Similar folds and, in addition, brecciated textures have been described from successions west of the Rift (Reuf, 1967; Kolodny, 1969; Steinitz, 1981) from the stratigraphically higher, chert-dominated, equivalents of the Amman Silicified Limestone.

Most authors agree that the process of brecciation, folding and cementation of Snatonian-Campanian cherts in the region occurred during early diagenesis (Steinitz, 1981; Fink and Reches, 1983). Alternating phases of cracking and cementation in cherts has been described (Simonson, 1987) where the cracking is attributed to synaeresis processes during dewatering of a gelatinous silica-rich sediment. Fink and Reches (1983) concluded that density inversions associated with early chert diagenesis, together with the influence of a regional, intraformational stress-field, were the cause of internal deformation and boudinage of chert layers, although we prefer gravitational instability as a secondary partial triggering mechanism. Steinitz (1981) suggested that volumetric changes could have occurred during silicification with a net influx of silica inducing internal folding. However, in the Wadi Mujib section silicification has not been total and some of the chert-rich beds remain porous and, furthermore, silicification of skeletal material is incomplete. We suggest that the degree of deformation of the chert-rich succession as a result of volume changes in the opal-A to opal-CT transition is related to the proportion of silica in the precursor sediment (Isaacs, 1982). This hypothesis is supported by the presence of highly brecciated chert fabrics and more intense penecontemporaneous folds in the overlying chert-dominated Amman Silicified Limestone (Powell and Moh'd, 2011, their figures 19 and 20) and its equivalent west of the Dead Sea Rift (Fink and Reches, 1983). Geochemical studies of coeval brecciated chert-rich sediments (Campanian Mishash Formation of Israel) suggest that the early-formed fragments in the chert breccia underwent early diagenesis in contact with sea-water, but the more porous, detrital-rich matrix was formed in contact with fresh-water (Kolodny et al., 1980; 2005). However, we have not found evidence of fresh-water indicators at the macro- or micro-scale and prefer a process of differential lithification of silica-rich versus silica-poor precursor marine sediments.

Microfossil Distribution

Deposition of planktic-neritic microfauna during Tafilah Member times appears to have varied from one area to another. Variations of bio-productivity during the Senonian on the mid- to inner-shelf zones of the Neo-Tethys in this region have been noted by Flexer and Starinsky (1970) and Flexer and Honigstein (1984); they suggest that the predominance of siliceous microfossils is indicative of shallower, shoreward locations, whilst the proportion of calcareous microfauna increases offshore. This trend fits well with the known lithofacies variations of the Wadi Umm Ghudran Formation in Jordan, where the chalk members thicken towards the west (offshore) at the expense of the chert/dolomite/siliciclastic association in south and east

Jordan (Powell, 1989). Furthermore, this pattern is also reflected within the middle Tafilah Member where carbonates, including chalky marls and concretions, are more common in the west (Jibal Khureij [pre-Rift], Mukawir and Edh Dhira) compared to the chert-dominated sequences in the east (Wadi Mujib, Tafilah areas) (Powell, 1988). The relative proportion of calcareous to siliceous microfauna thereby influenced the early diagenesis of the original laminated chalky-siliceous sediment on the Tafilah Member to produce replacive laminated cherts with chalky partings, at one extreme, and chalky marl with carbonate concretions, at the other.

Sea-level Fluctuations

The sequences described in this paper (Figure 10) provide new information on sea-level fluctuation in the hemi-pelagic and pelagic ramp of Neo-Tethys (Powell and Moh'd, 2011). Hardgrounds and overlying detrital, remanié phosphatic chalk at the base of thick Coniacian to early Campanian chalks (Mujib Chalk and Dhiban Chalk members and their correlatives in the Negev) mark depositional hiatuses resulting from a marked sea-rise during transgression. The omission surfaces and the overlying detrital phosphatic chalks are thought to represent co-planar transgressive and high-stand systems tracts (Figure 10). Upward passage to deeper-water, foraminiferal-coccolith pelagic sedimentation reflects maximum flooding of the ramp. The maximum flooding surfaces (mfs) within the chalk units associated with regional marine onlap may be equivalent to mfs recognised by Sharland et al. (2001; 2004) during the Early Coniacian K150 (88 Ma) for the Mujib Chalk Member, and Mid Campanian K 170 (78 Ma) for the Dhiban Chalk Member. Mixed chert, chalky marl, dolomite and chalky phosphorite sediments (Tafilah Member, separating these two chalk members) represents a regressive low-stand (Figures 9 and 10). These sediments pass shore-wards to mixed marine siliciclastics, dolomite and marl lithofacies representing littoral and coastal plain sediments (Powell and Moh'd., 2011).

CONCLUSIONS

Recognition of hardgrounds in hemi-pelagic chalk-chert-phosphorite associations aid the regional correlation of these lithologically-heterogenous sediments, and provide a wealth of information on sedimentation, timing of early diagenesis and sea-level fluctuation in the hemi-pelagic ramp setting of the Neo-Tethys Ocean during the Late Cretaceous.

Hardgrounds at the base of the Dhiban Chalk Member developed in the mid- to inner-pelagic ramp zones, located on the Levant and Arabian plates, at the southern margin of the Neo-Tethys Ocean. This regionally variable hardground surface developed during a phase of rapid sea-level rise and low sedimentation rate following deposition, early diagenetic lithification of silica, and deformation of the regressive (low stand), shallow-water, chert-dominated Tafilah Member, which in turn overlies the deeper water Mujib

Chalk. The hardground surfaces shows evidence of submarine erosion, endolithic bioerosion and corrosion of the substrate. The hardground surfaces were subsequently colonised, locally, by encrusting oyster bivalves or colonial corals. This was followed, in upward sequence, by detrital phosphatic chalk, representing a condensed sequence, and subsequently, by pelagic chalk. The chalk sequence above the hardgrounds indicates rapidly increased water depths and marine flooding during co-planar transgressive and high stand systems tracts on the ramp (Figure 10).

Beds below the hardground surface range from chert and/or tripoli with chalky partings to chalky marl with carbonate concretions. At Wadi Mujib, early diagenetic replacement of the original biogenic carbonate fraction comprising a mixed carbonate-silica ooze, by silica, had taken place prior to the gentle deformation of the chert, but subsequent to microscopic endolithic tunnel borings and phosphatisation of bone and shell fragments on the seafloor. The deformation of the chert-rich beds is thought to be the result volume changes and density inversion during very early diagenesis associated with the change from opal-A to opal-CT in the silica-rich beds; deformation may have been enhanced by down slope gravitational slumping on the homoclinal ramp.

Differences in the lithologies underlying the hardground at the Wadi Mujib and the other localities reflects regional variation, over the mid- to inner-ramp zones, of the relative proportion of calcareous to siliceous planktic-necktic microfauna; these variations influenced very early diagenesis of the precursor sediment. The relative paucity of omission and hardground surfaces in the region, as compared to European chalk succession is probably the result of the basin architecture (homoclinal ramp) that was conducive to more continuous sedimentation on the southern margin of the Neo-Tethys (Levant and Arabian plates). In this region ocean upwelling and organic productivity resulted in a more diverse siliceous (chert) and calcareous (chalk) microplankton productivity, coupled with, at times, higher production and preservation of phosphate (fish and marine reptiles) and preservation of phosphate and chert in low redox conditions on the seafloor.

The hardgrounds and overlying detrital, remanié phosphatic chalk at the base of Mujib Chalk and Dhiban Chalk members and their Coniacian to Campanian correlatives in the Negev reflect depositional hiatuses resulting from a marked sea-level rise. The chalk units are interpreteted as co-planar transgressive and high-stand systems tracts. Maximum flooding surfaces (mfs) within the chalk units associated with marine onlap may be equivalent to mfs recognised by Sharland et al. (2001, 2004) during the Early Coniacian K150 (88 Ma) for the Mujib Chalk Member, and Mid Campanian K 170 (78 Ma) for the Dhiban Chalk Member

Para now shortened (JHP) *[most of this paragraph is a repetition of the paragraph on Sea-level Fluctuations above, in the DISCUSSION section]*.

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FIGURE CAPTIONS

Figure 1: Map showing the location of sections mentioned in the text, the general lithofacies belts (Coniacian to Campanian) and the left lateral offset of Jibal Khureij along the Dead Sea Rift Fault (DSF).

Figure 2: Stratigraphical subdivision of the Late Cretaceous succession in the Levant region.

Figure 3: Summary geological sections at Wadi Mujib, Wadi Abu Khusheiba and Jibal Khureij showing the position of the hardground (Hg) at the base of the Dhiban Chalk Member, and correlation of the Late Cretaceous succession along the Rift margin (note lateral offset of the Jibal Khureij section, located west of the main Dead Sea Fault; see Figure 1). WSL = Wadi Sir Limestone.

Figure 4: Late Cretaceous succession and hardgrounds: (a) Wadi Mujib (view of southern escarpment); the lower part of the Wadi Mujib section is the Early Cretaceous Kurnub Sandstone; most of the section is represented by the Ajlun Group platform carbonates; the major sequence boundary (drowning unconformity) between the Ajlun (AJ) and Belqa groups is marked SB at the top of the Wadi Sir Limestone (WSL) overlain in upward sequence by the Mujib Chalk (MC), Tafilah Member (TF), Dhiban Chalk (DC), the chert-rich Amman Silicified Limestone (ASL) and the Al Hisa Phosphorite (AHP). The rim of the escarpment is capped by dark Pleistocene basalt (PB). Total section ca. 900 m.

(b) Mukawir section, showing the rimmed carbonate platform sequence, Ajlun Group (AJ), overlain by the pelagic ramp sequence (Belqa Group). SB marks the platform drowning sequence boundary. The white-weathered lower (Mujib) and upper (Dhiban) chalks are clearly seen, separated by the darker heterolithic Tafilah Member; the dark, wavy bedded cherts above the Dhiban Chalk Member belong to the Amman Silicified Limestone (ASL); note the penecontemporaneous chert folds (arrowed).

(c) Annotated photograph showing the hardground and overlying Dhiban Chalk Member truncating underlying gently-folded chert-rich heterolithic

Tafilah Member; hammer length 0.35 m, in same position as (d); Wadi Mujib section.

(d) Close-up photograph of (c) showing the colonial octocoral bioherms (OC), overlying the folded bored and corroded chalky marls and chert beds (Tafilah Member). Detrital, phosphatic chalk, above the coral colonies passes up to more massive chalk (hammer length 0.35 m).

(e) Exhumed bored concretions from the hardground at Jibal Khureij showing numerous cup-shaped *Lithophaga* bivalve borings, some infilled with detrital phosphate, on its upper surface; note the absence of borings on the underside of the concretions; hammer length 35 cm; uppermost Tafilah Member, Jibal Khureij.

(f) Small concretion from the Edh Dhira area showing *Lithophaga* borings infilled by detrital phosphatic chalk on the upper surface. The lens cap (5 cm diameter) marks the boundary between the Tafilah Member and the overlying Dhiban Chalk Member.

Figure 5: Polished slab of detrital chalk from Wadi Mujib showing, in order of decreasing size, octocoral (oc) revealing major septa and individual corallites (medium to dark grey), phosphatic bone fragments (p) (pale grey), 'floating' in a matrix of chalk (white) with fine-grained bone and shell fragments. Sample from 0.02 m above the hardground surface, Wadi Mujib.

Figure 6: (a) Silicified coccolith (arrow) and authigenic silica crystals, uppermost Tafilah Member, Wadi Mujib. Scanning electron micrograph. Scale bar = 5 μm.

(b) 'Tripoli' microfabric showing clusters of authigenic silica crystals, probable recrystallised coccolith tests (arrowed), and abundant porosity; uppermost Tafilah Member, Wadi Mujib. Scanning electron micrograph. Scale bar =10 μm.

(c) Phosphatised fish and marine reptile bone fragments (white) and shell fragments showing phosphatisation and endolithic tunnel borings; mid-grey areas are chalk matrix and detrital chalk fragments; black areas are chlorapatite. Basal detrital chalk, Dhiban Chalk Member, about 0.02 m above the hardground surface. Backscattered scanning electron micrograph. Scale bar = 400 μm.

(d) Coccolith plates and fragments showing abundant porosity, pelagic Dhiban Chalk, 4 m above hardground, Wadi Mujib. Scanning electron micrograph. Scale bar = 10 μm.

(e) High contrast backscattered electron micrograph showing globulose borings within a bone fragment. The excavated cavities contain small particles of phosphate. The bone is surrounded by finely crystalline silica or tripoli (medium grey) with numerous small pores (black). uppermost Tafilah Member, Wadi Mujib. Scale Bar = 100 µm.

(f) Partly phosphatised mollusc (?oyster) fragment showing one side riddled with algal microborings. The fragment is entombed in a dark chalk matrix. Dhiban Chalk Member, Wadi Mujib. Thin section micrograph, transmitted light. Scale bar = 100 µm.

New **Figure 7**: (a) High contrast backscattered electron micrograph showing phosphatised shell (white) with growth lines (pale grey) and partly silicified bivalve shell (uniform medium-grey) with pore space (dark grey) preserving shell growth lines. The matrix comprises mostly small phosphate fragments and spherules with silica. Uppermost Tafilah Member, Wadi Mujib. Scale bar = 200 µm.

b) High contrast backscattered electron micrograph enlargement of (a) showing authigenic silica (uniform medium-grey) enveloping phosphate fragments (white) and forming thin replaced zones along the growth lines of the former shell (shape indicated by dissolution porosity, dark grey to black. In places the silica occurs as single or clustered spherules (medium-grey). The bright granular bands near the base are microfossil ooze comprising calcitic microfossils and small phosphate fragments. Uppermost Tafilah Member, Wadi Mujib. Scale bar = 100 µm.

(c) Thin section photomicrograph showing phosphatised shell fragment (probably a bivalve) with a thin peripheral coating of authigenic silica (white); the replacive phosphate has a low birefringence and is nearly isotropic. Uppermost Tafilah Member, Wadi Mujib. Scale bar = 200 µm.

(d) Thin section showing dolomite rhombs with a simple pattern of zoning under cathodoluminesence, generally with a non-luminescent core, and a red-luminescent outer rim. A red-luminescent central zone is present in some of the dolomite rhombs. The enveloping microquartz is non-luminescent, a feature that is characteristic of authigenic quartz. Uppermost Tafilah Member, Wadi Mujib. Scale bar = 100 µm.

e) Two generations of calcite crystals infilling voids left after the dissolution of former shells (probably aragonitic) are filled by two generations of calcite cement. The first and earliest is non-luminescent and preserves the scalenohedral or blocky crystal forms of the initial cement phase; the second shows a moderately bright, orange-yellow luminescence, which is faintly zoned and tends to fully occlude the remaining void space. Uppermost Tafilah Member, Wadi Mujib. Scale bar = 100 µm.

Figure 8 (was 7): Conceptual model for sedimentation and the development of the hardgrounds at the base of the Dhiban Chalk in Wadi Mujib/Mukawir and, in contrast, at Jibal Khureij/Edh Dhira. See Figure 3 for an explanation of symbols.

Figure 9 (was 8): Sedimentation model for the deposition of pelagic and hemi-pelagic calcareous and siliceous oozes on the pelagic ramp in Late Cretaceous times. The Wadi Ghudran Formation succession is shown just above the sequence boundary (SB) between the Ajlun and Belqa groups. See Figure 3 for an explanation of the symbols. After Powell and Moh'd (2011).

Figure 10 (was 9): Coniacian to Campanian sequence-stratigraphical interpretation and inferred sea-level curves, based on the Wadi Mujib section. See Figure 3 for an explanation of lithological symbols. WSL = Wadi As Sir Limestone; ASL = Amman Silicified Limestone; SB = Sequence Boundary; msf = Maximum Flooding Surface; HST = Highstand Systems Tract; LST = Lowstand Systems Tract.