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Formation Mechanisms of Some Features in Siliceous Upper Cretaceous-Lower Tertiary Beds of Jordan-Undulations, Geodes, Boudinages

Elias Salameh*, Hani Khoury

Department of Geology, University of Jordan, Amman, Jordan
Email: *salameli@ju.edu.jo

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Abstract

Geode, boudinage, and undulation structures are widely distributed in the siliceous beds of the Upper Cretaceous/Tertiary rocks in Jordan. Their formation was attributed to tectonic forces, syngenetic processes, organic disintegration processes, subaquatic gliding, compaction and settlement, and meteoritic impacts. In this work, the structural features in the siliceous beds of Jordan are attributed to an interplay of load and directed pressures, and mineralogical transformation processes (opal-A to opal-CT to quartz), governed by pH changes. Tectonic directed pressure was acting in an ESE-WSW direction and is common in the silicified limestone of Upper Cretaceous.

Keywords

Undulations, Geodes, Boudinages, Opal-A, Porcelanite, Chert Transformations, pH Changes, Stress Fields, Jordan

1. Introduction

Distinctive structures of undulations, geodes and boudinages are present in the chert beds of the Upper Cretaceous/ Lower Tertiary rocks in Jordan [1]-[6] among others). The formation mechanisms of these structures were attributed to syngenetic processes [7] tectonic forces [1] [2], volume increase due to organic disintegration processes [8], subaquatic gliding [3] [8], seismic activity [9] [10], compaction and settlement [11] [12] and meteoritic impact [13]. Geological mapping of the different structures in the Shoulder Mountains on both sides of the Jordan Rift Valley has revealed a sequence of subaquatic gliding (due to the plasticity of the sediments) that was associated with seismic activity and sloping topography towards the sinking Jordan Rift Valley Depression [3].

The following work explores other mechanisms, than what have been suggested by the above studied and research articles for the formation of undulation, boudinage, and geode structures in the cherty beds of the Upper Cretaceous-Early Tertiary sedimentary rocks of Jordan. The study aims at clarifying the mechanisms of the formation of the mentioned structures, which, until now, have formed a riddle for scholars.

2. Stratigraphy of Upper Cretaceous-Early Tertiary Beds

The stratigraphy of Central Jordan with emphasis on Upper Cretaceous-Lower Tertiary Formation is described in **Table 1** [14].

Chert-porcelanite layers and beds with boudinage, and geode structures are present in the Cenomanian Na'ur and Fuheis Formations (**Figures 1-3**). Chalk marl, limestone, dolomite, phosphatic chert, and silicified limestone beds over- and underlie the chert-porcelanite beds.

Undulating chert-porcelanite beds and layers of different thicknesses are typical to the Campanian/Maastrichtian Silicified Limestone Formation (**Figure 1(a)**, **Figure 1(b)**, **Figure 2(b)**). Boudinage structures (thin interrupted chert beds) are found in the Eocene Chalk Marl (B4, 5 Units).

The undulations, geodes and boudinage structures disappear rapidly in the overlying and underlying formations (**Figure 1**). These structures die out vertically (in case of undulations) (**Figure 3**) and horizontally (in case of boudinage and geodes) in a few tens of decimeters (**Figure 2**).

3. Chert-Porcelanite Beds in Jordan

Chert-porcelanite in general is of biogenic origin, although it might occur as chemical precipitate from oversaturated aqueous solution with respect to H_4SiO_4 or because of diagenetic replacement of limestone. Opal-A, or amorphous silica

Table 1. Stratigraphy of Cretaceous-Tertiary rocks in Central Jordan (After [14] open files).

Age	Formation	Type of rocks	Thickness (m)
Eocene	Chalk Marl B4/5	Chalk marl and chert	Up to 150
Cretaceous-Tertiary	Bituminous Marl B3	Bituminous Marl	Only in small outcrops
Campanian Maastrichtian	Um Ghudran Silicified Limestone B1/2	Silicified limestone overlain by chert beds	Around 70 m
Turonian-Santonian	Massive Limestone A7	Massive sandy limestone	55 m
Cenomanian	Na'ur A1/2, Fuheis A3 Hummar A4, Shueib A5/6	Alternating beds of limestone, dolomite, marly limestone, dolomitic limestone, sandstone, marl and some gypsum layers and evaporate residues	Around 300 m
Deep sandstone aquifer system	Lower Cretaceous-Precambrian	Coarse, medium and fine-grained sandstone	1450 - 1600 m

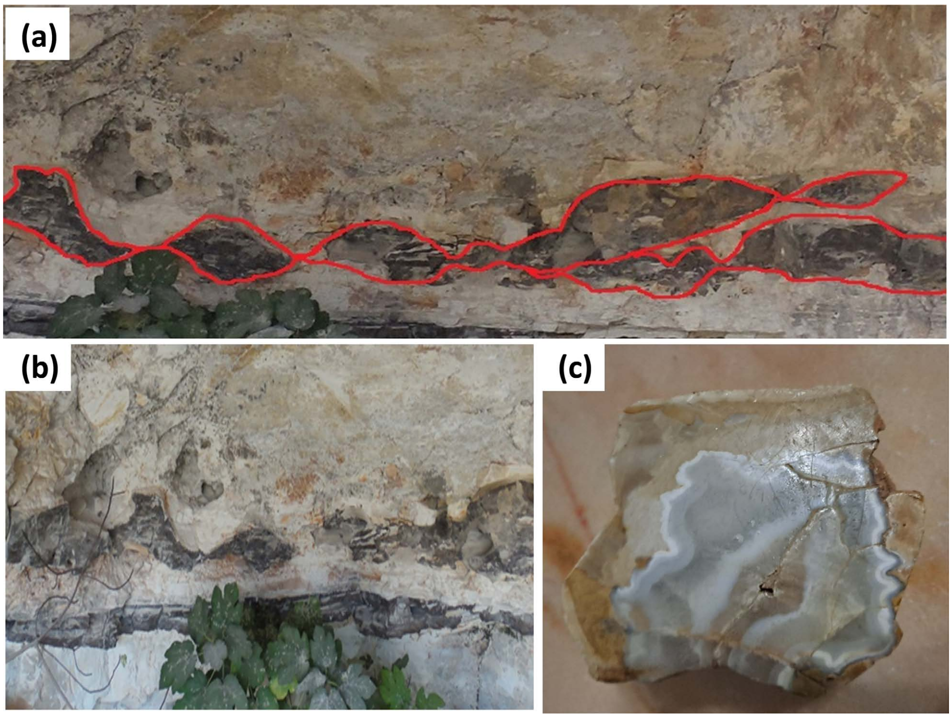

Figure 1. Chert beds with boudinage and geode structures: ((a), (b)). Boudinage structures (thin interrupted chert beds) disappear rapidly in the overlying and underlying beds and horizontally in a few tens of decimeters, (c). Geode showing silica layering from towards euhedral quartz to the center.

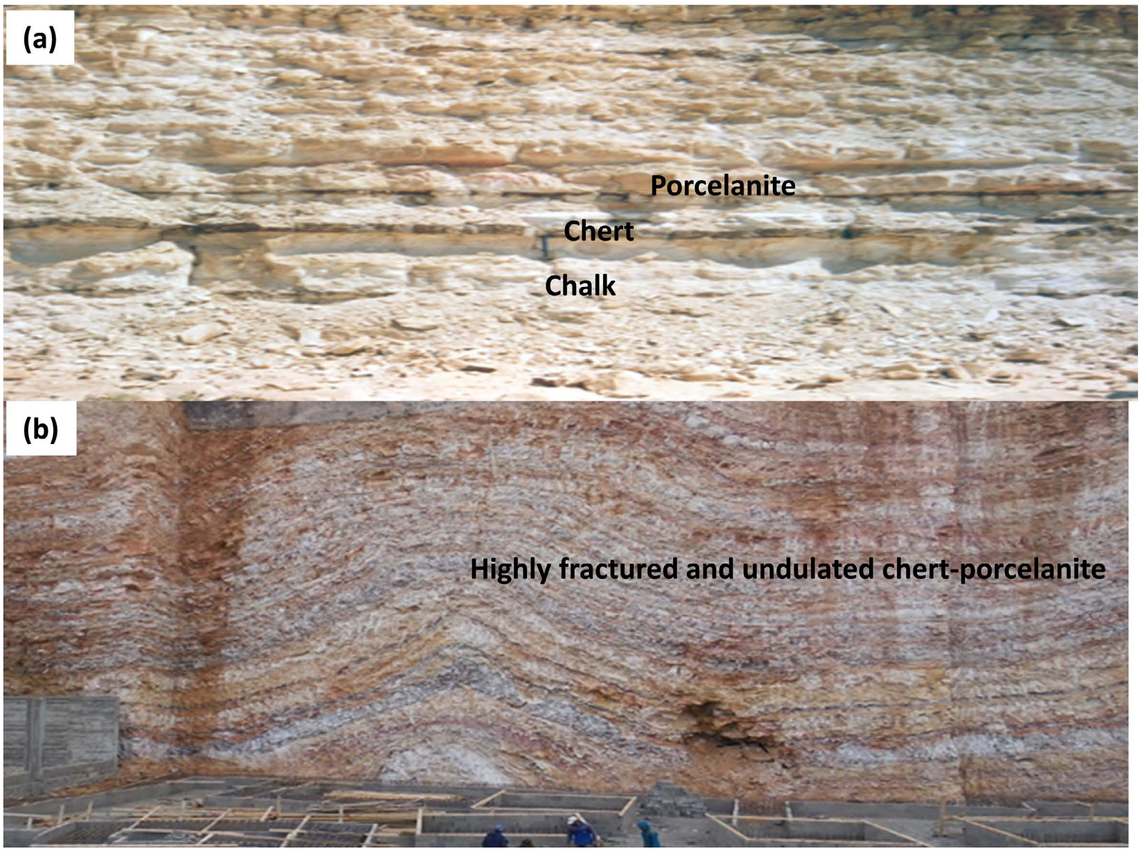

Figure 2. Highly fractured chalk-chert-porcelanite beds (a), Horizontal (b). Undulated.

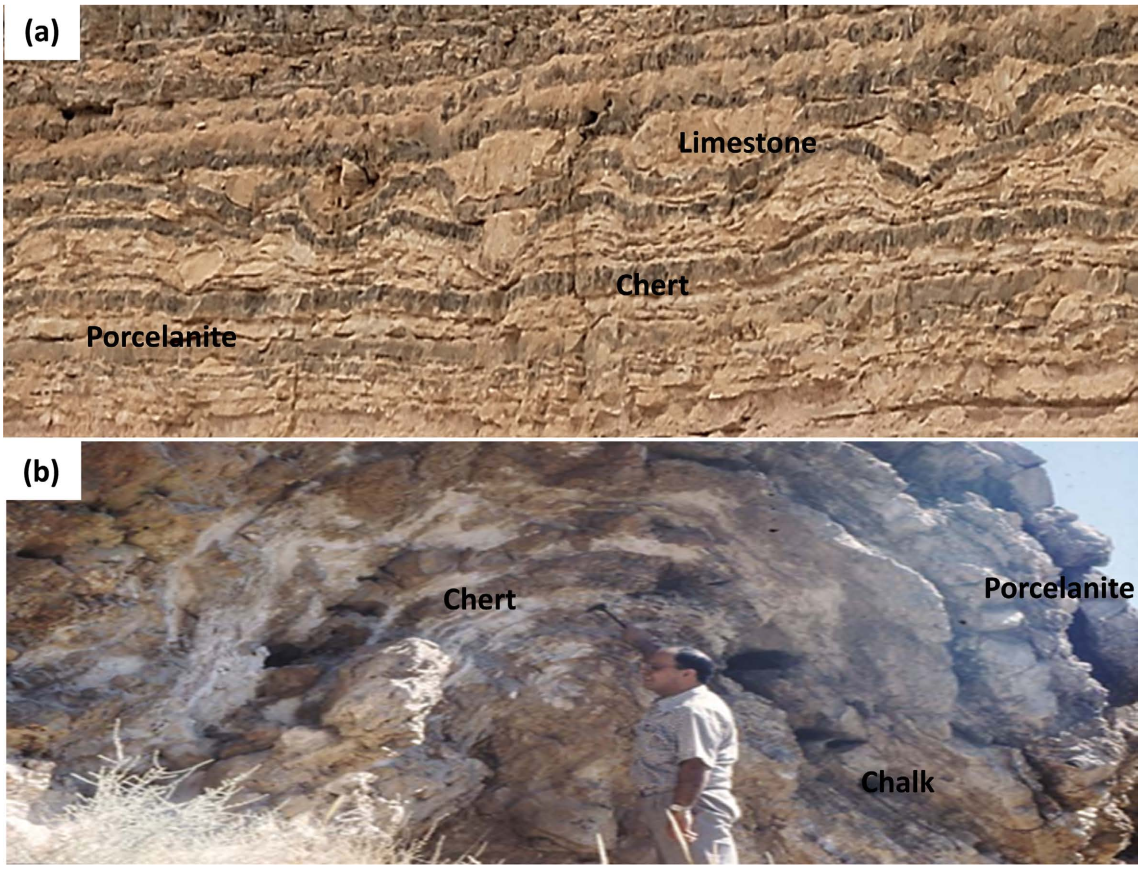

Figure 3. Distinctive undulation structures in siliceous beds. Undulations are common in both chert and porcelanite beds: (a) Undulations die out vertically, (b) Highly undulated chert-porcelanite beds.

[$SiO_2 \cdot nH_2O$, $Si(OH)_4$]) is the composition of skeletal fragments of siliceous organisms such as diatoms, radiolarian, siliflagellata, sponge spicules and many others [15] [16]. The high phosphate and silica concentration in the up-welling oceanic currents (eutrophic water, with a $pH > 7.5$) has led to the precipitation of the phosphate and siliceous sediments in Jordan [15].

Amorphous silica is unstable with a low density (1.98 - 2.2 g/cm^3) and fine grain size (8 - 10 microns [17] [18]. Decrease in temperature and pH and increase in pressure transform Opal-A gradually into metastable opal-CT (cristobalite and trydimite) with a higher density (2.2 - 2.3 g/cm^3), and finally into quartz with a density of 2.55 - 2.91 g/cm^3, and size > 20 microns. Chert-porcelanite are the main fate of buried siliceous ooze and permanently the removal of silica from the oceanic silica cycle [17]-[23].

Fluctuations in the pH values (acidic and alkaline) are responsible for the dissolution/precipitation of silica in solution. Decrease in the pH-values results from the production of CO_2, NO_x, and eventual SO_2 because of bacterial reduction of dissolved O_2, nitrates and sulfates from the siliceous beds. Volcanic activity can also contribute in increasing acidity of the water by releasing gases such as HCl, HS, and CO_2 [15]. Cretaceous Large Igneous Provinces have caused a decrease in the pH-values of the water and the deposited sediments that enabled transformation processes of a variety of minerals such as opal-A, glauconite, and illite [15].

The transformation process from amorphous silica to crystalline silica (quartz) reduces the volume by around 22%. The increase of load pressure (overburden) because of continuous sedimentation leads also to reduction in volume of the accompanied siliceous amorphous sediments. Deformation and reduction in thickness of the siliceous beds take place in a vertical direction. Lateral changes (shrinkage) need not to take place in the siliceous beds because of the high viscosity of the amorphous silica that keeps the siliceous beds intact. Distinctive structures of geodes, boudinages and undulation are present in the chert and porcelanite beds of the Upper Cretaceous/ Lower Tertiary rocks in Jordan Upper. In the area NW of Amman, geodes, boudinage, and intact chert layers (no undulations) are present in the same formation.

Geodes are common in the Nodular Limestone Unit and interfinger laterally with chert lenses (boudinages) and chert beds within the same layer (**Figure 1(c)**). The highly viscous amorphous silica has high surface tension and low affinity relative to the surrounding calcareous precipitates [24]. During the first transformation process of hydrous amorphous silica (opal-A) to cristobalite-tridymite (opal-CT) (lower density than the calcareous rocks), thinner beds of amorphous silica separate the amorphous silica layers and form clusters (clumps, lenses) of different sizes, up to a few decimeter in diameter within the same layer. The borders of the silica gel clusters in the calcareous rocks are usually very sharp and indicate early formation of silicate rock [23] [24]. Intact siliceous clusters (starting geodes), transformation to opal C-T (crystallization and consolidation) starts from the outside as a result of decrease of the pH-values. Opal C-T surrounds the forming geode and separates it from the surrounding calcareous sediments allowing herewith its gradual transformation to stable quartz towards the voids at the center [5]. The crystallization of geodes has clearly begun from the outer side to the inner side (concentric layers) to euhedral quartz crystallizing from silica-rich solution in the cavity of the geodes (**Figure 1(c)**).

Boudinage structure is common in the disturbed chert beds. It is mostly related to the mineral transformation processes of amorphous siliceous ooze (opal-A) to cristobalite-tridymite (opal C-T) (to form porcelanite) and finally to cryptocrystalline –microcrystalline quartz (to form chert), accompanied by reduction in volume and shrinkage forming disturbed irregular clusters.

Undulations or meso-foldings are the result of the reaction of rocks to lateral compression pressure actively affecting the whole formation. Undulations are the result of the inability of rocks to move laterally but vertically to form undulations. Two mechanisms have worked simultaneously to form the undulations: compressional forces (related to lateral compression) and mineral transformation processes. Regional lateral forces have affected the competent chert-porcelanite beds by folding (forming undulations) and the incompetent overlying and underlying calcareous beds by forming internal flowage. Undulations were restricted to the chert-porcelanite beds and not to the overlying and underlying calcareous beds of the Upper Cretaceous Formations of Jordan and Palestine.

4. Discussion

Two simultaneous mechanisms (tectonic and mineral transformation) have affected the chert-porcelanite beds in Joran.

The tectonic factor was active where a stress field has affected the Levant area during Maastrichtian time in an ESE-WNW, 130˚ - 140˚ direction [2]. Prominent horizontal-peak stylolites in the Upper Cretaceous Formations indicate a stress field striking in the same direction; 130˚ - 140˚, especially in the Massive Limestone Unit (Wadi Sir Formation) of Campanian-Maastrichtian age [25], which underlies the highly undulated Silicified Limestone Formation (Amman Formation). Horizontal stylolites are related to stress fields acting parallel to the stylolitic peaks [26] [27].

Alhejoj [28] found deformed fossils in the limestone beds of the Upper Cretaceous rocks, stressed in the same ESE-WNW direction, especially in the Wadi Sir Formation. The stress field has preceded the deformation of the fossils and the horizontal stylolites. Moreover, the deformation indicates the presence of competent compacted siliceous layers that reacted rigidly, while the overlying and underlying incompetent soft calcareous sediments were in a lithification stage, allowing the development of stylolites. The vergence of the folding planes of the chalk-porcelanite-chert layers in a WNW direction indicates ESE direction stress field [3]. The vergence direction of the undulating chert beds on both sides of the Jordan Rift Valley is the same and coincides with the stress field that produced the deformation of fossils [28], the stylolites [25], and some mega structures in the Levant [2].

The mineral transformation factor was effective because of pH-value fluctuations. The bituminous marls of the Muwaqqar Formation that overlie the undulated beds were deposited in a eutrophic sea with high organic activity (high pH water), that percolated down into the siliceous beds. The change of the pH values because of volcanic activities has lowered the pH below 8 and eutrophication activities have increased the pH to more than 9. The high pH water values have facilitated the dissolution of opal-C-T and the transformation to opal-A. The transformation processes of the siliceous beds led to the increase in volume and decrease in density (from −2.65 to −2.3 g/cm^3). However, lateral expansion of the siliceous beds to accommodate that increase in volume seems to have been restricted by the huge friction with the over- and underlying ductile calcareous rocks (extending horizontally for tens of kilometers). The easiest way for the siliceous beds to expand seems to have taken place by undulating in a vertical direction (Ϭ3). The combination of the tectonic stress field and the expansive stress resulting from the mineralogical transformation process (both as Ϭ1) seem to have been relieved by the formation of undulations (in Ϭ3 direction) striking in a NNE-SSW direction (Ϭ2); the strike direction of the undulations.

Another factor that was related to the increase of pH is the spontaneous combustion processes of the bituminous marls that overlie the Silicified Limestone Formation (containing the undulating chert beds The combustion process have produced alkaline water with pH of more than twelve that circulated down through joints and fissures to the siliceous beds [29]. The down percolating high pH water has facilitated the mineral transformation of opal-C-T to opal-A to quartz.

The temporarily prevailing alkaline conditions must have ended when the organic-activity- and the oil shale combustion-high pH waters stopped reaching the underground siliceous rocks and the organic matter in the oil shale started to disintegrate under anaerobic conditions producing acidic gases such as CO_2 and HS. In addition, magmatic gases (including volcanic gases) such as HCl, HF, HS, CO_2, irrespective of their quantities, affect rocks in the underground and therefore, the alkaline conditions ended. Under these new conditions, the opal-A beds produced under alkaline conditions started to dehydrate again to form opal-CT and quartz. The transformation process was accompanied by reduction in volume, which manifests itself by cracking and splintering of the chert and porcelanite beds.

The horizontal stress caused by the silica transformation processes and the concomitant regional tectonic stress field (Ϭ1) both acting in an ESE-WNW direction could have produced the splintering and brecciation of the rigid undulating porcelanite-chert beds after their final transformation processes (**Figure 4**). Strong earthquakes could also have produced them. In addition, they can result from increasing the load pressure on the shrining fragile siliceous beds, which were under transformation. Meteoritic impacts such as Waqf as Suwwan Crater could have also contributed to the formation of the splintering and brecciation of the chert beds [13].

5. Conclusions

A combination of tectonic forces acting in an ESE- WNW direction (Quennell 1959) and mineral transformation mechanisms (opal-A to opal-CT to quartz

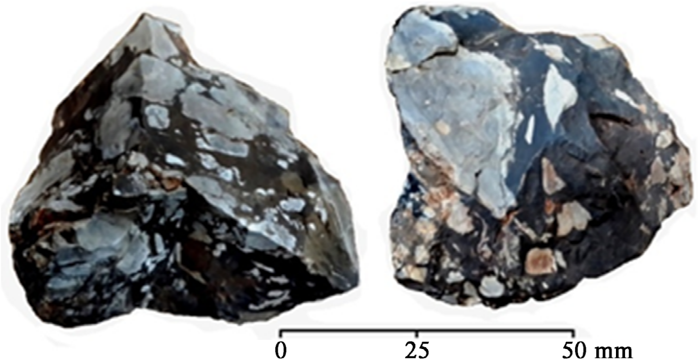

Figure 4. Meteoritic impacts such as Waqf as Suwwan Crater could have also contributed to the formation of the splintering and brecciation of the chert beds (Salameh *et al.*, 2006).

and vice versa) are considered responsible for the formation of the geodes, boudinage and undulation structures. This study concludes that the formation of these structures in the chert-porcelanite beds of the Upper Cretaceous/Tertiary rocks in Jordan is a result of an interplay between load pressure (overburden), tectonic stresses (directed pressure), and mineral transformation processes. Mineral transformations were accompanied by changes in volume of up to 22% because of opal-A transformation to Opal-C-T accompanied by reduction in volume and rehydration of opal-C-T under increasing pH accompanied by increases in volume. These processes resulted in the formation of local undulations in the very widely spread siliceous beds extending for hundreds of kilometers.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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