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Grain size analysis of the Lower Cambrian–Lower Cretaceous clastic sequence of Jordan: Sedimentological and paleo-hydrodynamical implications

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ABSTRACT

356 sand-sized samples ranging in age from Early Cambrian Epoch to Late Cretaceous Epoch of known depositional environments were analyzed mechanically to obtain the grain size parameters of mode, median, mean and sorting.

The constructed grain size distribution curves for the various Paleozoic and Mesozoic formations were interpreted in terms of the paleo-hydrodynamic processes prevailing through transportation and deposition.

The study proved that the grain size parameters of sand-sized sediments most sensitive to paleo-depositional environmental recognition were the graphic mean grain size and the inclusive graphic sorting.

Mean grain size values below 1.77 ϕ of a sand-sized sample could indicate a fluvial channel paleo-depositional environment, whereas the mean grain size values above 2.8 ϕ are indicative to a shallow marine paleo-depositional environment. Sorting values above 1.1 ϕ may indicate a fluvial channel paleo-depositional environment.

A bivariate discriminatory plot of mean grain size versus sorting yields two fields that can successfully discriminate between the fluvial channel paleo-depositional environment, and the shallow marine paleo-depositional environment.

A new grain size parameter, termed the mean–sorting index, was introduced in this study and calculated by dividing the mean grain size value over the sorting value. It is recorded here that the mean–sorting index is more sensitive to paleo-depositional environment recognition than the individual mean grain size and sorting parameters.

1. Introduction

Grain-size analysis (GSA) as a tool to infer the provenance, the sedimentary processes, the sediment transport pathways, and to determine the paleo-depositional environments for clastic sedimentary rocks documented in the stratigraphic record flourished in the first six decades of the last century (Udden, 1898; Wentworth, 1929; Folk and Ward, 1957; Friedman, 1961, 1967; Krumbein and Graybill, 1965; Griffiths, 1967). This granulometric method is based upon comparison of the textural properties of ancient sediments with those of recent sediments gathered from modern sedimentary environments.

The climax of GSA approach began to decline in mid of the 1970s, where some workers considered the findings of GSA to be inadequate and unsatisfactory (Boggs, 1987), others questioned the informational value of GSA studies (Reed et al., 1975; Law, 1980).

Therefore, there is now a decline and fragmentation of GSA. Instead, GSA is currently devoted to understand and construct models for the sedimentary morphodynamic process-response systems by engineers aiming to control sediment movement through designing special structures (Hartmann and Flemming, 2007). Also, during the last two decades GSAs were applied by sedimentologists to determine the sediment transport pathways (Le Roux and Rojas, 2007; McLaren et al., 2007), to determine the dynamic behavior of bottom sediments with respect to erosion, accretion, or dynamic equilibrium (McLaren et al., 2007), and in coastal research and management (Winter, 2007).

However, some sedimentologists still have a firm commitment to GSA and consider it fundamental to the understanding of sedimentary processes and products, as well as being a basic tool in both academic Earth sciences, through providing valuable information on provenance, transport mechanism, and depositional

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environment, and also in applied scientific Earth sciences (Bagnold and Barndorff-Nielsen, 1980; McLaren and Bowels, 1985; Hartmann, 1991, 2007; Flemming and Ziegler, 1995; Weltje and Prins, 2007; Cheetham et al., 2008). Moreover, textural graphic parameters (mean grain size, median, mode, sorting, skewness and kurtosis) are still in use, as reflected in modern publications, textbooks and classroom lectures (Hartmann, 2007).

Sedimentologists try to extract genetic information concealed in grain-size distribution curves (GSDs) by applying various methods, such as conceptual inverse modeling or numerical inverse modeling (Weltje and Prins, 2007), where the sedimentological processes and initial conditions can be gained from the final product which is a set of measured GSDs with their temporal–spatial coordinates (Weltje and Prins, 2007).

The temporal–spatial variations of GSDs reflect variation of dynamics of the transporting medium through time and space, for example spatial variations along the pathway from source to basin. They may originate, besides the variation of provenance, transport mechanism, and evolution of the depositional environments mentioned above, through a mechanism of mixing of sediments dispersed from several sources. The mixing of elementary populations, or distinct subpopulations, is evidenced by presence of polymodal GSDs of some sediment.

Estimation of the elementary populations can be done by various analytical, graphic and numerical approaches (Curray, 1960; Clark, 1976; Ashley, 1978; Shih and Komar, 1994; Wohletz et al., 1989; Sun et al., 2002). All of these approaches try to decompose or un-mix the polymodal GSDs into various types of elementary populations or unimodal end members in order to understand the mechanisms of the GSDs of natural sediments based on the popular theoretical models (Weltje, 1997; Weltje and Prins, 2007; Holtz et al., 2007; Le Roux and Rojas, 2007).

The basic assumption underlying (un)mixing models of polymodal GSDs is to regard each GSD measured at a given temporal–spatial coordinates as a mixture of sediment populations each indicating a specific hydrodynamic process (Visher, 1969; Middleton, 1976; Bridge, 1981).

However, the GSDs of the Lower Cambrian–Lower Cretaceous of Jordan under investigation are entirely unimodal, thus any method of the listed above used in partitioning polymodal sediments is unnecessary and was not applied in the present study.

The present study aimed at applying the graphic grain size parameters on the Lower Cambrian–Lower Cretaceous clastic sequence of Jordan of already known paleo-depositional environments to attest the validity of these grain size parameters in determining paleo-depositional environments of other clastic sequences registered in the stratigraphic record. To extract the sedimentological morphodynamic and hydrodynamic processes acting through transportation and deposition of the various Palaeozoic and Mesozoic formations concealed in the GSDs represented another goal of the study.

2. Geologic setting

A 2500 m-thick clastic and carbonate sequence ranging in age from Early Cambrian Epoch to Late Cretaceous Epoch crops out in certain parts of Jordan (Fig. 1; Table 1). The Paleozoic Erathem consists of the entire Cambrian System, entire Ordovician System and lowermost part of the Silurian System (Table 1).

The Cambrian System and the lower part of the Ordovician System are called the Rum Group and consist of the following formations arranged in an ascending stratigraphic order: Salab Formation, Abu Khusheiba Formation, Umm Ishrin Formation, Disi Formation and Umm Saham Formation. The other part of the Ordovician System and the lowermost part of the Silurian System are termed the Khreim Group and consist of the following formations arranged in an ascending stratigraphic order: Hiswa Formation, Dubaydib Formation, Mudawwara Formation that is comprised of four members: Tubailiyat Member, Ammar Member, Batra Member, and Ratya Member, and Khusha Formation.

The remaining part of the Silurian System as well as the Devonian and the Carboniferous Systems are not represented in Jordan (Bender, 1968). Most probably, they were truncated through the Hercynian Orogeny (Saint-Marc, 1978) that affected the region during the Carboniferous Period, as indicated from the presence of strata of Late Paleozoic age in adjoining countries. Just the uppermost part of the Permian System is cropping out in central western Jordan.

The Mesozoic Erathem is represented in Jordan by carbonates and clastics of the Triassic and Jurassic Systems, a predominating siliciclastic sequence of the Lower Cretaceous Series called the Kurnub Group, and carbonates, evaporites, cherts, oil shales and phosphorites of the Upper Cretaceous Series.

Since the present study is concerned with grain size analysis, only the clastic Lower Paleozoic sequence and the clastic Lower Cretaceous sequence are the subject of investigation.

The Lower Cambrian clastic strata start non-conformably above the Neoproterozoic metamorphic, intrusive and extrusive basement complex in southern and south western Jordan. Predominant sandstones, with much less abundant conglomerates and silt-mudstones constitute the basal fluvial Cambrian Salab Formation and the overlying fluvial-dominated Umm Ishrin Formation. On the other hand, shallow marine, better sorted sandstones constitute the Abu Khusheiba Formation that represents the north-west facies variation of the lower part of the latter two formations. The deeper marine, regional, Burj Formation covalent of the Abu Khusheiba Formation crops out in the most north western part of the study area and consists mainly of carbonates with subordinate sandstones and mudstones.

The Ordovician System (Table 1) is more marine-influenced and consists mainly of sandstones with minor silt-mud stones, but lacks the carbonate deposits. The sandstones of the Disi Formation, the lower Ordovician formation, start conformably above the Umm Ishrin clastics without a distinct stratigraphic boundary. Only a gradational change of color form reddish brown characteristic to Umm Ishrin sandstone to white-colored Disi deposits demarcates this contact. Amireh et al. (2001), based upon the first appearance of *Cruziana furcifera*, documented the boundary between the Cambrian and Ordovician Systems to be located 130 m above this contact. Besides this shallow marine event, other three short incursions of the Tethys Ocean, giving rise to different *Cruziana* species and other ichnofossils, interrupted the fluvial-dominated Disi Formation (Bender, 1968; Amireh, 1987; Amireh et al., 2001).

The Umm Saham Formation, the second Ordovician formation, consists of a sandy fluvial-dominated lower part and a finer clastic upper part deposited in an intertidal environment (Amireh et al., 2001). The intertidal conditions were replaced by a deeper marine environment during deposition of the overlying third Ordovician Hiswa Formation. It consists of a lower part composed of fine sandstone deposited in the upper shoreface zone that grades upwardly into fine sandstone and mudstone of the upper part deposited in a deeper lower shoreface to offshore environment. The Dubaydib Formation, the fourth Ordovician formation, consists of fine to very fine sandstone facies alternating with siltstone facies and was deposited within the upper to lower shoreface zone (Amireh et al., 2001). Fluctuation between the upper-to lower shoreface and the open marine offshore conditions persisted through deposition of the overlying Tubailiyat, Batra, and Ratya Members of the fifth Ordovician Mudawwara Formation. This is also applied on the last overlying Lower Silurian Khusha Formation. Various types of ichnofossils are pervasive throughout the latter four marine formations.