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Estimating palaeo-water depth from the physical rock record

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ABSTRACT

Palaeo-water depth and its change with time is a key factor in environmental analysis and in sedimentology in general. The literature published on this topic and on related subjects, however, is substantial albeit scattered within and between different communities (geologists, oceanographers, engineers, physicists etc.). Here I focus on proxies for palaeo-bathymetry as obtained from the physical rock record. Floral, faunal and chemical evidence for palaeo-water depth, being equally important, must be dealt with elsewhere. An assessment of the main depth-related parameters in actualistic settings is presented and their applicability to the fossil sedimentary record discussed. The outcome reveals the full complexity of this topic. There is, for example, no such thing as an average wave-base depth applicable to a wide range of fossil case settings. This because wave and current climates in general, and particularly so in neritic and coastal settings, are intriguingly complex. Furthermore, observations from modern oceans are not a priori applicable to fossil ones. Acknowledging these problems and limitations, critically evaluated quantitative proposals for depth indicative facies and features in the sedimentary record are presented and error bars discussed.

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1. Introduction

Water depth (or bathymetry) is a fundamental parameter of any subaquatic sedimentary environment. In conventional terms, depth implies the vertical interval at a point between two specific interfaces or discontinuities: one being the sediment–water and the other being the water–atmosphere interface (Allen, 1967). Attempts to reconstruct palaeo-water depths from the fossil rock record are usually referred to as "palaeo-bathymetry". The term "bathymetry" is derived from the Greek "βαθυς", *deep*, and "μετρον", *measure*. In other words, bathymetry is the study of underwater depth, of the third dimension of lake or ocean floors, whereas palaeo-bathymetry aims at establishing past water depths from the geological record.

Early techniques for measuring water depths used pre-measured heavy rope or cable lowered over a ship's side. Today, the bathymetry of oceans and lakes is commonly quantified by means of an echosounder (sonar) mounted beneath or over the side of a vessel, "pinging" a beam of sound downward at the seafloor. The amount of time it takes for the sound to travel through the water, bounce off the seafloor, and return to the sounder tells the equipment how far down the seafloor is. Modern multibeam echosounders, mounted on research vessels (Krastel et al., 2001; Roberts et al., 2005), are featuring dozens of very narrow adjacent beams arranged in a fan-like swath and provide very high resolution topography maps and the resulting seafloor bathymetry. Alternatively, a radar altimeter mounted on an orbiting spacecraft (Sandwell et al., 2006) can efficiently measure slight variations in ocean surface height and hence seafloor topography and bathymetry.

Geologists, however, dealing with ancient limnic or oceanic deposits, their coastal settings and ancient epicratonic seas cannot make use of such techniques and depend on estimates based on a series of features recognized in the rock record. These features, although cornerstones in palaeo-bathymetric interpretation, are subject to limitations as proxies for palaeo-water depth. Various methods reconstructing palaeo-water depth have been proposed but none is universally applicable (Allen, 1967; Hallam, 1967; Eicher, 1969; Benedict and Walker, 1978; Sundquist, 1982; Clifton, 1988; Brett et al., 1993; ten Veen and Kleinspehn, 2000; Della Porta et al., 2002a,b; Immenhauser and Scott, 2002; John et al., 2004; Ryan et al., 2007). Occasionally, a geological situation is encountered in which a direct quantification of absolute palaeo-waterdepth is possible. In this case, the gross geometrical and altitudinal relationship between two exposures of the same formation, or between different formations, is visible in outcrop or can be inferred from subsurface data (Newell et al., 1953; Swann et al., 1965; Shelton, 1965; Soreghan and Giles, 1999; Bahamonde et al., 2004; van der Kooij et al., 2007). This situation is, however, the exception rather than the rule. Most workers use (and combine) sedimentological, lithological, taphonomical, biological or chemical evidence and their typically association with specific water depths as observed in modern marine or lacustrine environments and apply these findings to fossil case settings. Here, the focus is on sedimentological parameters.

I wish to make clear that this paper does not address larger issues of palaeo-bathymetry in general but rather serves the reader by providing a general overview and introduction to palaeo-waterdepth hindcasting from the physical rock record. Consequently, the aim of this paper is to provide a practical and relatively jargon-free guide for non-specialistic (field) geologists, as well as sedimentologists, sequence stratigraphers and those concerned with palaeo-environmental analysis and back-stripping studies of sedimentary successions. The paper is organized as follows: the first part (Sections 2 and 3) introduces to those hydrodynamic processes that relevant for the interpretation of sediment transport under waves and currents and the formation of related bedforms. This is essential reading for those concerned with palaeo-water depth estimates. The second part (Section 4) summarizes the bathymetry of present-day neritic carbonate and siliciclastic settings in a brief manner. The third part (Section 5) describes and discusses diagnostic facies and features that are of significance for palaeo-water depth reconstruction. A tentative separation in (i) relative, (ii) semi-quantitative and (iii) quantitative palaeo-water depth indicators is proposed. The later ones, and particularly reconstructions of wave climates from vortex ripples, are given priority as they allow for a rather rigorous hindcasting of past water depths. An overview of bathymetric ranges for depth-indicative facies and features within their relative error bars is shown in Table 1. Extensive lists of references for further reading are presented in each section.

2. Ancient seas and modern analogues

Two major types of marine water bodies are commonly separated: (1) Open oceanic (pelagic) seas, covering oceanic lithosphere, and (2) epicontinental seas, covering continental lithosphere (see references in Immenhauser et al. (2008). Epicontinental seas today (and through geologic time) again fall into two broad categories: (2a) Epeiric–neritic seas that are open or semi-enclosed basins extending into the interiors of continents. In the modern world, these include for example the Yellow Sea, the Adriatic Sea, the North Sea, the Persian Gulf or the Gulf of Carpentaria. (2b) Open, peri-continental shelves that are marginal to all continents and more common today than during past glacial periods because of the Holocene rise in sea level (Fig. 1; Nittrouer and Wright, 1994). Presently, marginal and coastal seas cover about 10% of the global sea surface.

Wave-base depths and current patterns in open marine, peri-continental/coastal and epeiric–neritic seas are often not comparable. Coastal neritic and epeiric neritic waters (less than 150–200 m deep) have features that are sufficiently distinctive from deep oceans or deep epeiric basins (bathyal/abyssal domain; Fig. 2). These differences include a variety of processes composing a highly complicated picture of the sea surface, the wave spectrum and the related depth of the wave base. The influx of freshwater run-off from the land has the effect of modifying the salinity, and hence also the physical properties of coastal waters. As a result, coastal waters are usually areas of relatively large horizontal gradients of water density often associated