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Invited review

Sedimentary condensation

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ABSTRACT

The term "*condensation*" has been used in sedimentological research for 180 years and ever since the last 80 years, its interpretation has become increasingly diverse and, to a certain degree, also divergent. The result is that today, the different definitions are not always compatible and therefore useful. It is for this reason that the term "*condensation*" is newly defined here, using the original descriptions from before 1930 and a new interpretation of condensed sediments, which were the subject of the first monograph dedicated to condensation (Heim and Seitz, 1934).

Condensed sediments are present in mostly well individualized, extremely thin (<1 m) beds, which were formed during extremely long time periods (>100 ky), and which experienced authigenesis and the precipitation of glaucony, verdine, phosphate, iron and manganese oxyhydroxides, iron sulfide, carbonate and/or silica. They usually show complex internal stratigraphies, which result from an interplay of sediment accumulation, halts in sedimentation, sediment winnowing, erosion, reworking and bypass. They may include amalgamated faunas of different origin and age. Hardgrounds may be part of condensed beds and may embody strongly condensed beds by themselves.

Sedimentary condensation is the result of a hydrodynamically active depositional regime, in which sediment accumulation, winnowing, erosion, reworking and bypass are processes, which alternate as a function of changes in the location and intensity of currents, and/or as the result of episodic high-energy events engendered by storms and gravity flow. The definition proposed here excludes the use of the term "*condensed*" in sequence-stratigraphic approaches, unless condensed beds as defined here are present. The term "*condensed*" in a sequence stratigraphic sense may be replaced by "*sediment starved*".

Sedimentary condensation has been and still is a widespread phenomenon in past and present-day oceans. The present-day distribution of glaucony and verdine-rich sediments on shelves and upper slopes, phosphate-rich sediments and phosphorite on outer shelves and upper slopes, ferromanganese crusts on slopes, seamounts and submarine plateaus, and ferromanganese nodules on abyssal seafloors is a good indication of the importance of condensation processes today. In the past, we may add the occurrence of oolitic ironstone, carbonate hardgrounds, and eventually also silica layers in banded iron formations as indicators of the importance of condensation processes. Besides their economic value, condensed sediments are useful both as a carrier of geochemical proxies of paleoceanographic and paleoenvironmental change, as well as the product of episodes of paleoceanographic and paleoenvironmental change themselves.

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"*... das Problem der submarin entstandenen Diskontinuitäten und der Kondensation ist von allgemeiner, die Erde umspannender Bedeutung*": "*… the problem of discontinuities of submarine origin and condensation is of general importance, concerning the entire Earth*": Heim and Seitz, 1934, p. 307

"*Condensed sections play a fundamental role in stratigraphic correlation, both regionally and globally*": Loutit et al., 1988, p. 183

1. Introduction

The term "*condensation*" is generally used to describe the transformation of a substance from its gaseous phase into a liquid phase (like water vapor into water), for instance along solid surfaces (like a window). In a more inclusive approach, "*condensed matter*" physics deals with the physical properties of solid and liquid phases in general. A more special case is the use of the term "*condensed*" in everyday life, where it describes high-viscosity fluids like "*condensed milk*", which results from the selective removal of water. Less well known to non-specialists is the use of the terms "*condensation*" and "*condensed*" in sedimentological and stratigraphic approaches. There, in its broadest sense, "*condensation*" implies the process of sediment deposition in regimes of generally reduced accumulation rates. The corresponding term "*condensed sediment*" denotes a deposit, which is thin and has formed during a long time period.

Sedimentary condensation is a widespread phenomenon in present-day oceans and condensed sediments occur in a large array of settings, which range from the inner shelf to the abyssal seafloor. It is useful to identify and analyze condensed sediments as they provide information on hydrodynamic and hydrochemical conditions, ecology, bathymetry, sea level, tectonic and volcanic activity, and oceanographic and environmental conditions in general during their deposition. They represent also an economically important resource of authigenic minerals and associated elements like phosphate and ferromanganese oxyhydroxides.

The terms "*condensation*" and "*condensed*" have been used in stratigraphic and sedimentological studies for at least 180 years, and during this time interval, both terms have seen an evolution towards an increasing diversity in their definitions. Distinction is presently made between "*facies condensation*" (Lombard, 1956), "*environmental*", "*biotic*" and "*diagenetic condensation*" (Fürsich, 1978), "*mechanical*", "*chemical*" and "*biological condensation*" (Fels and Seyfried, 1993; Flügel, 2004), "*event condensation*" (Seilacher, 1985, 1992), "*taphonomic*", "*stratigraphic*" and "*sedimentary condensation*" (Fernández-López and Gómez, 1991; Gómez and Fernández-López, 1994; Fernández-López et al., 2002), and last but not the least, "*condensation*" in seismic and sequence stratigraphic applications (Loutit et al., 1988). As we will see from the following chapter on the history of the use of the term "*condensation*" and "*condensed*" beds, the evolution of these terms reminds one of a diversification pattern, which developed through multiple bifurcations into a complex network, where each line represents a particular type of condensation (Fig. 1).

This results in the circumstance that today, the terms "*condensation*" and "*condensed sediment*" are applied in different and partly incompatible ways. Depending on the type of definition, the term "*condensed sediments*" may be used for shallow-water shell accumulations, phosphatic conglomerates and hardgrounds, concretion horizons, and pelagic sediments, among other types of sediments, and their thickness may vary between a few centimeters and hundreds of meters. The present-day richness in definitions renders the proper use of the terms difficult and a new approach is necessary, in order to save the terms and provide them with an appropriate place in stratigraphic and sedimentological terminologies. It is hence the goal of this contribution to trace the history of the use of the terms "*condensation*" and "*condensed*", to review and revise the definition of the two terms and to propose a clear set of sedimentological, mineralogical and paleontological criteria to identify and define "*condensed*" beds, and finally to emphasize the importance of identifying and interpreting "*condensed*" sediments as indicators of paleoceanographic and paleoenvironmental change.

2. The history of the terms "*condensation*" and "*condensed*"

2.1. The first users (1830–1930)

In sedimentological textbooks and publications, Heim (1934) invariably appears as the oldest reference with regards to sedimentary condensation (e.g., Mensink, 1960; Jenkyns, 1971; Fürsich, 1978; Fels and Seyfried, 1993; Flügel, 2004; Schlager, 2005). This circumstance neglects the fact that already in the 19th and early 20th centuries, the term "condensed" was used in a sedimentological sense in the Anglo-Saxon and French literature. The word "condensed" does not appear

Fig. 1. Evolution and diversification of the term "*condensed*" as a function of time and language. This diagram is far from perfect in that publications other than those written in English, French and German were not considered. The use of the term condensed can also be traced in the Spanish literature ("*condensación*"; e.g., Fernández-López and Gómez, 1991), in the Polish literature ("*kondensacje*"; e.g., Szulczewski, 1978), and likely in many other languages. Publications in French and German are considered here as they show a long history in the use of the term "*condensed*".