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Introducing the Xenoconformity

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Abrupt vertical changes are commonplace in sedimentary sequences and a basis for how we subdivide the stratigraphic record. These stratigraphic shifts may be obvious, such as when they are manifested in sharp differences in lithology or an erosional surface, or they may be subtle, such as when they are represented in the turnover of fossil assemblages or changes in geochemical signatures. Commonly, these abrupt changes correspond to an unconformity, which is a stratigraphic surface that represents a break in sediment accumulation, often accompanied by erosion. Unconformities are as important as the strata themselves in interpreting geological history.

Less common but arguably equally important in reconstructing geological history are surfaces that result from dramatic shifts in environmental conditions. Familiar examples are many major boundaries of the geological time scale such as the Permian-Triassic and Cretaceous-Paleogene (K-Pg) boundaries. In addition to the loss of a large number of fossil taxa, the K-Pg boundary is clearly identified by an Ir anomaly (Alvarez et al., 1980; Smit and Hertogen, 1980), a decrease in carbonate content, and a negative carbon isotope anomaly (Hsü et al., 1982). It is intuitive that state changes in paleoenvironments, as exemplified by the K-Pg boundary, occur both globally and regionally and that these changes can generate unique surfaces or transition zones that can be correlated widely. Nonetheless, while clearly understood that these stratigraphic surfaces exist, the geological lexicon lacks a term to describe them. In this issue of *Geology*, Carroll (p. 639) has taken the first step in correcting this semantic oversight by introducing the term *xenoconformity*, defined as "a stratigraphic surface or gradational interval that records a fundamental, abrupt, and persistent change in sedimentary facies across basinal to global scales."

In sedimentary geology, the term *facies* refers to a suite of lithological, physical, and biological features of a sediment or sedimentary rock that can be used to distinguish it from other sediments that occur laterally or rocks that occur above or below (Walker, 1992). The principal of uniformitarianism, coupled to observations of modern environments, allows sedimentologists to link facies preserved in the sedimentary record to depositional process. By extension, a suite of facies can be combined into a unique *facies association*, which represents a specific depositional environment, such as a tidal flat, lagoon, or delta front. The theoretic framework by which geologists then read Earth history from the stratigraphic record is provided by Walther's Law, which elegantly asserts that vertically juxtaposed and conformable facies associations in sedimentary sections reflect laterally adjacent environments at the time of deposition (Walther, 1893; Middleton, 1973).

Walther's Law is a simple yet powerful tool, and it laid the foundation for the development of sequence stratigraphy, a method of stratigraphic analysis that emphasizes using changes in facies and stratal geometries to reconstruct the chronological history of basin fill and erosion (Catuneanu et al., 2009). Central to this approach is the recognition that shifts in stratal stacking patterns result from changes in the interplay between sediment supply and the generation or destruction of accommodation space for those sediments (Catuneanu et al., 2009). These changes generate unique sequence stratigraphic surfaces, such as the subaerial unconformity (SU), maximum regressive surface (MRS), and maximum transgressive surface (MTS). These surfaces are useful both for making correlations on a basinal scale and for parsing how time is partitioned in the stratigraphic fill of that basin.

Application of sequence stratigraphy is *de rigueur* in the modern study of sedimentary basins and their depositional records. However, as Carroll (2017) points out, neither sequence stratigraphy nor Walther's Law accounts for the juxtaposition of contrasting facies association that results from rapid environmental change rather than the gradual shoreward or basinward drift of depositional environments. The shortcomings of traditional gradualistic approaches are particularly evident in lacustrine systems because lakes are highly sensitive to changes in water balance and sediment supply (Scholz and Finney, 1994). Carroll uses the Eocene Green River Formation of Wyoming (USA) to demonstrate the definition of a xenoconformity and the rationale for this neologism. In the Green River Formation, three distinct facies associations are identified: fluvial-lacustrine, fluctuating-profundal, and evaporative, corresponding, respectively, to hydrologically open (fresh water), fluctuating (i.e., flooding and desiccation), and saline conditions (Carroll and Bohacs, 1999). Although these facies associations are superimposed conformably in vertical sections, contrary to Walther's Law, they do not represent coexisting, laterally adjacent environments. Rather, each facies association reflects a distinct state of the lacustrine system governed by regional water balance and manifested in water depth, sediment supply, and salinity. Consequently, switches between these facies associations record fundamentally distinct paleoenvironments, driven by external factors, such as the vagaries of regional climate or tectonics. These abrupt paleoenvironmental switches generate a distinct surface or transitional interval that develops rapidly with respect to the timescale over which the succeeding facies endures—a key component in Carroll's definition of a xenoconformity and its utility in stratigraphy. Importantly, this definition excludes surfaces that develop as a result of short-term sedimentary events, such as tsunamis or turbidity currents, because although they may juxtapose strongly differing facies and be visually striking, these events do not result in a persistent shift in paleoenvironment.

Although less common, xenoconformities are developed in the marine realm as well. As in the case of the K-Pg boundary, these surfaces in marine strata represent catastrophic perturbations or "tipping points," the environmental consequences of which are global in scale and can manifest in any combination of the physical, chemical, and biological character of the sediments. The key is that these changes can be identified globally in sediments deposited in many different settings. In this regard, xenoconformities double as marker horizons in that they define an essentially isochronous surface that can be widely traced stratigraphically. The opposite is not true: not all marker horizons are xenoconformities. For example, a widely distributed tephra layer, such as that deposited following the massive Toba eruption in Sumatra at 73 ka, is a valuable stratigraphic tool and also corresponded to a massive environmental perturbation (Ninkovich et al., 1978; Williams et al., 2009). However, the global environmental effect following the eruption was geologically transient and not long-lived.

The Paleocene-Eocene boundary is another key example of a marine xenoconformity. In deep-sea cores, this boundary is identified by a sudden disappearance or decline of carbonate content (due to rapid shoaling of the calcite compensation depth; Zachos et al., 2005), and in both marine and terrestrial settings, it is recorded by a sharp negative carbon isotope anomaly and abrupt warming (Kennett and Scott, 1991; Koch et al., 1992). By analogy with the current rise in pCO_2 and other rapid anthropogenic environmental changes, Earth's most recent xenoconformity, separating the Holocene below from the Anthropocene above, is in the process of forming. The question is where, precisely, this surface will be placed in the sedimentary record (Smith and Zeder, 2013)

Another quintessential example of a xenoconformity is the base of the "cap dolostone" that marks the end of late Cryogenian (i.e., Marinoan) snowball glaciation at ca. 635 Ma and represents a virtually geologically instantaneous switch from deposition of glacial to carbonate facies. Because the cap dolostone was deposited diachronously during the post-glacial transgression (Hoffman et al., 2007), it occurs widely across continental shelves, and the xenoconformity at its base can be recognized even where subjacent glaciogenic strata are absent (in this case, the xenoconformity variably corresponds to a MRS or a SU, and the MTS occurs above the cap dolostone). So impressive, distinct, and widespread is this xenoconformity that it is used to define the base of the Ediacaran Period (Fig. 1) (Knoll et al., 2006). It is both an exceptional chronostratigraphic marker and a cogent reminder of the importance of non-actualistic processes in shaping the stratigraphic record.

Only time will tell whether the xenoconformity will be embraced by stratigraphers and incorporated into their already jargon-rich lexicon. One challenge lies in the fact that its application is prone to controversy over the interpretation of the nature, severity, and timing of paleoenvironmental changes. Another challenge is that xenoconformities, unlike other important stratigraphic surfaces, are not scale-independent and how they will be integrated into the sequence stratigraphic framework is not yet evident. Nevertheless, the concept of a surface that defines a state change in paleoenvironments, with obvious implications for styles and rates of sedimentation, should enhance our ability to delineate and interpret the stratigraphic record.

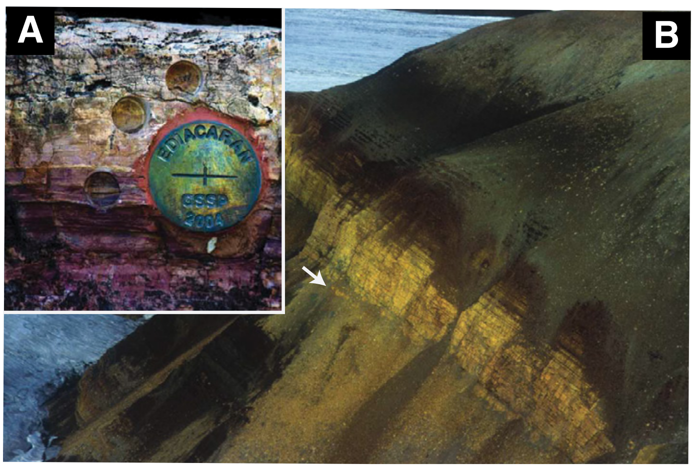

Figure 1. A: The xenoconformity at the contact between the glaciogenic Elatina Formation below and the Nuccaleena cap dolostone in Brachina Gorge (Flinders Ranges, South Australia) was chosen as the Global Stratotype Section and Point (i.e., GSSP or "golden spike") for the ca. 635 Ma base of the Ediacaran Period (Knoll et al., 2006). B: This same surface can be identified with confidence globally, including in Svalbard, where it marks the contact (white arrow) between the Cryogenian Wilsonbreen Formation and the Ediacaran Dracoisen cap dolostone.

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