Palaeogeography, Palaeoclimatology, Palaeoecology 444 (2016) 48–59

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Buried or brined? Eurypterids and evaporites in the Silurian Appalachian basin

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ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form 10 December 2015
Accepted 13 December 2015
Available online 21 December 2015

Keywords:
Salina/Bertie groups
Eurypterus
Salt hopper
Diagenesis
Arthropod paleoecology hypersalinity

ABSTRACT

Eurypterid-bearing deposits from the late Silurian Appalachian basin are often interpreted as having been deposited under hypersaline conditions. These interpretations are based on the close association of abundant eurypterid remains with evaporite deposits and structures such as salt hoppers in the Salina and Bertie groups. To determine whether this association reflects life habitat, or is the result of taphonomic or diagenetic processes, the co-occurrence of eurypterids and salt hoppers in the upper Silurian Appalachian basin was examined at several stratigraphic scales. A survey of eurypterid remains from the prolific Ellicott Creek Breccia Member of the Fiddler's Green Formation (Bertie Group) found that 2% of the 479 specimens surveyed are crosscut by salt hoppers or incipient halite structures. In a regional survey, displacive salt hoppers occurred in the same bed as eurypterid remains in 37% (19:51) of all eurypterid-bearing units. In these units, salt hoppers were typically the only structures found intimately associated with eurypterids, sometimes crosscutting them. The disruptive nature of the hoppers in the Ellicott Creek Breccia, for example, suggests that they formed within the sediment rather than at the air-water interface, and that organic remains might have acted as nucleation points for developing halite crystals. To explain these associations, we present a depositional model in which displacive salt hoppers formed within NaCl-saturated groundwater as a result of surface evaporation in the vadose zone during regressive phases, and only after eurypterid remains were buried. In this scenario, the intimate association of eurypterids and salt hoppers in these deposits reflects early-stage diagenetic overprinting rather than conditions during life. Our model largely refutes the hypothesis that eurypterids were halotolerant organisms based on their co-occurrence with salt hoppers. We conclude that eurypterids preserved in upper Silurian carbonate ramp deposits were primarily denizens of more normal marine or hyposaline subtidal settings.

1. Introduction

The habitats of the Eurypterida (Arthropoda: Chelicerata) have long been disputed. Although there now appears to be a consensus that eurypterids underwent a marine-to-freshwater transition during the Late Ordovician–Devonian (Lamsdell and Braddy, 2010; see O'Connell, 1916; Plotnick, 1999; Braddy, 2001, for reviews), the preferred habitat and salinity tolerance of many individual groups during this period remain unresolved. Recent work has refined our view of the taxonomic basis for this transition into terrestrially dominated settings (Lamsdell and Braddy, 2010), but a lack of constraint on the habitat range of many eurypterid lineages remains. Without these basic paleoecological details, it is difficult to ascertain not only the drivers behind this environmental transition, but also the drivers of eurypterid extinctions that began in the end-Silurian and culminated in the end-Devonian mass extinction (Lamsdell and Braddy, 2010).

Among these transitional taxa are eurypterids from the upper Silurian–Lower Devonian Salina, Bertie, and lowest Helderberg groups of the Appalachian basin of Laurentia. Here, abundant and well-preserved eurypterids and other fauna are frequently found in calcareous shales and argillaceous, chemically precipitated dolomites ("waterlimes"), deposited in what is generally considered to represent the subtidal–supratidal zone of a shallow lagoonal or sabkha-like environment on the margin of a gently dipping epeiric sea (Ciurca, 1973; Smosna et al., 1977; Belak, 1980; Hamell, 1982; Tollerton and Muskatt, 1984; Ciurca, 1990; Bell and Smosna, 1999). Despite general agreement on the depositional environment, determination of the specific paleosalinity (i.e., brackish [hyposaline], normal marine [euhaline], or hypersaline–briny) and eurypterid habitat in these settings is complicated by the co-occurrence of eurypterids with putative terrigenous flora, and normal marine and euryhaline fauna (Tollerton, 1997, and references therein; Plotnick, 1999, and references therein; Braddy, 2001;

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http://dx.doi.org/10.1016/j.palaeo.2015.12.011
0031-0182/

Burrow and Rudkin, 2014; McKenzie, 2014; Nolan, 2014; Vrazo et al., 2014b; SJC, personal observations), in units that frequently either lack defining sedimentology at the bed level (cf. Alling and Briggs, 1961; Leutze, 1961) or contain indicators of extreme hypersalinity, i.e., evaporitic salt hoppers (Ciurca and Hamell, 1994).

Because halite structures are formed under evaporative, hypersaline conditions (Dellwig, 1955; Arthurton, 1973; Southgate, 1982), their intimate association with eurypterids in nearshore deposits has led to the assertion by some authors that eurypterids (and other early chelicerates, e.g., scorpions; Kjellesvig-Waering, 1966) probably inhabited these conditions, and/or were euryhaline (e.g., Clarke and Ruedemann, 1912; Alling and Briggs, 1961; Størmer, 1976; Kluessendorf, 1994; see Braddy, 2001). However, implicit within this view is the requirement that eurypterids tolerated far higher salinities than any modern marine chelicerate.

In this study, we aim to determine the likelihood for eurypterid inhabitance, or burial, in hypersaline environments by examining the depositional relationship of eurypterids and salt hoppers at several stratigraphic scales, from locality to regional-level. Surveys of eurypterid–salt hopper associations provide empirical evidence for the respective timing of eurypterid burial and associated evaporite formation, and whether or not these structures should be considered indicative of habitat salinity. Based on these results, we present a new depositional model to explain the co-occurrence of eurypterids and evaporites in the Appalachian basin, and discuss its implications for eurypterid life habitats and preservation in the mid-Paleozoic.

2. Geologic setting

2.1. Appalachian basin stratigraphy

Laurentian epicontinental seas during the mid-Paleozoic were frequently evaporitic (Rickard, 1969). In the Appalachian basin, restricted oceanic input, a low latitude position, and a warm, arid climate led to the formation of evaporite deposits often hundreds of meters thick in the basin depo-center (Alling and Briggs, 1961; Dennison and Head, 1975; Smosna et al., 1977; Van der Voo, 1988). These evaporite deposits are represented by subsurface formations in the Salina Group lettered A–F (Rickard, 1969). Nearshore carbonate ramp environments in the northern Appalachian basin (New York and Ontario) are represented by exposures in the Syracuse and Camillus Formations (Salina Group) and the entire Bertie Group (Fig. 1). To the south, in Pennsylvania, Maryland, and West Virginia, this ramp setting is represented by the more argillaceous Wills Creek and Tonoloway Formations (Tourek, 1970 unpublished; Bell and Smosna, 1999). The Bertie Group contains none of the thick evaporite deposits seen in the Salina Group and, evidently, the basin was less prone to significant evaporite formation than it had been during Salina deposition. However, the basin still became hypersaline or briny during Bertie Group deposition, as indicated by the presence of thin evaporite layers such as the gypsum beds in the Forge Hollow Formation, and various evaporitic structures (Tollerton and Muskatt, 1984; Ciurca and Hamell, 1994).

2.2. Paleosalinity

Paleosalinity in the carbonate ramp settings of the upper Silurian Appalachian basin has been interpreted as ranging from brackish to hypersaline or briny. Brackish conditions are usually inferred from circumstantial evidence such the presence of terrestrial flora, a paucity of euhaline marine fauna and bioturbation, and the presence of apparently euryhaline, hyposaline-tolerant taxa such as gastropods, brachiopods, ostracods, and leperditicopid arthropods (e.g., Kjellesvig-Waering, 1950; Leutze, 1961; Plotnick, 1999; Vannier et al., 2001; Edwards et al., 2004; Vrazo et al., 2014b). Lingulate brachiopods are often found with eurypterids and are suggestive of eu- or hyposalinity as none have been identified in unequivocally hypersaline settings. The extinct ostracod-like arthropod *Leperditia* is particularly abundant in some mid-Paleozoic eurypterid assemblages, and is thought to have been both highly halotolerant and resistant to desiccation (Vannier et al., 2001). However, leperditicopids are frequently found in isolation on bedding planes within subaerially exposed sabkha-like intertidal–supratidal zones (e.g., in the Tonoloway Formation; Smosna et al., 1977; Warshauer and Smosna, 1977; Vrazo et al., 2014b), suggesting that they were more tolerant of evaporative conditions than other contemporaneous arthropods, including eurypterids. Eurypterids themselves have previously been used as indicators of hyposalinity in some settings, but it has since been argued that, in the absence of other sedimentological evidence, such interpretations may be erroneous because of their euryhaline tendencies (Selden, 1984; Braddy, 2001).

Unlike brackish conditions, hypersalinity in Appalachian basin nearshore deposits is unequivocally indicated by evaporitic structures such as gypsum beds, casts, and vugs, salt hoppers or halite molds/casts, and desiccation features, e.g., desiccation cracks, that occur throughout the Salina Group and suprajacent Bertie Group (Hamell, 1982; Hamell and Ciurca, 1982; Tollerton and Muskatt, 1984; Ciurca and Hamell, 1994). Salt hoppers and early-stage halite molds/casts (i.e., flat-faced cubic halite impressions lacking the characteristic hopper shape; see below) are among the most common sedimentary features in these intervals and both types of structure frequently occur on the same bedding planes as eurypterids (Tollerton and Muskatt, 1984; Ciurca and Hamell, 1994; Ciurca, 2013; see below), sometimes even crosscutting them or other organic structures. This close eurypterid–evaporite association has led some authors to suggest that pervasive hypersalinity may have been conducive to the excellent preservation of eurypterids and other fauna in the Bertie Group (Leutze, 1961; Kluessendorf, 1994; Edwards et al., 2004; Vrazo and Braddy, 2011; Ciurca, 2013). Although unwilling to make any definite claims regarding eurypterid salinity tolerance, Leutze (1961) went as far as to suggest that high salinity in the Salina Group may have occasionally created a “pickling brine”, preserving tissue that was otherwise unlikely to survive bacterial degradation. Because of the particularly close association of salt hoppers with eurypterids, we will focus on their development below.

2.3. Salt hopper development

Salt hoppers are hopper-shaped crystalline structures made from evaporitic minerals (halite) that occur in both ancient and modern settings. The term “hopper” refers to the stepped, pyramidal shape that is formed as the mineral precipitates outward from the edge, rather than center, of a crystal core. Salt hoppers are only one of several types of halite structure that have been found in Laurentian evaporite deposits and should not be confused with chevron halite, for example (Dellwig, 1955; Arthurton, 1973). Hopper-shaped halite crystals have been shown to form experimentally both at the air-water interface in saturated sodium chloride (NaCl) brines (Dellwig, 1955; Arthurton, 1973; Southgate, 1982) and within the water column (Sloss, 1969) as a result of surface evaporation. In the field, these are traditionally interpreted as having formed in evaporitic brine pools (e.g., Southgate, 1982). If halite crystals, either as an isolated hopper or as part of a floating crystalline raft, become too large to be kept buoyant by surface tension, they will drop down to the substrate and continue to grow as bottom growth crystals if the water column is completely saturated (Dellwig, 1955). Salt hoppers may also grow within the sediment if sodium chloride-saturated brines laterally penetrate the phreatic or vadose zone of subaerially exposed deposits (Gornitz and Schreiber, 1981). Evidence for displacive intrasedimentary salt hopper growth in the subsurface has been noted in modern or sub-Recent basins (Gornitz and Schreiber, 1981), sabkhas (Shearman, 1978), and salt pans and lakes (Handford, 1982; Lowenstein and Hardie, 1985), and in ancient marine sediments (Leitner et al., 2013).