Palaeogeography, Palaeoclimatology, Palaeoecology 271 (2009) 292–300

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

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

Discovery of agglutinated benthic foraminifera in Devonian black shales and their relevance for the redox state of ancient seas

Jürgen Schieber

Department of Geological Sciences, Indiana University, Bloomington, IN 47405, USA

ARTICLE INFO

Article history:
Received 24 June 2008
Received in revised form 4 October 2008
Accepted 31 October 2008

Keywords:
Black shale
Redox
Devonian
Anoxia
Bottom water oxygenation
Benthic foraminifera
Carbon burial
Carbon cycle

ABSTRACT

Agglutinated foraminifera are benthic organisms that occur in marginal marine to bathyal environments. Though some taxa can live in oxygen deficient environments, they require at least some oxygen in order to persist at the seafloor. The discovery that they occur widely in Late Devonian black shales has a bearing on the boundary conditions required for episodes of extensive carbon sequestration in marine sediments and their connection to atmospheric composition and global climate. Devonian black shales of the eastern US have been studied extensively to determine the fundamental controls on carbon burial, and a range of mechanisms has been proposed. Finding agglutinated benthic foraminifera in these black shales refocuses the debate about their origin and points to limitations of earlier models.

1. Introduction

The Late Devonian is notable in Earth history because of a mass extinction event (Hallam and Wignall, 1997) and globally extensive formation of black shales (Klemme and Ulmishek, 1991). The latter marks the onset of a substantial rise in atmospheric oxygen that culminated approximately 290 m.y. ago and is linked to the Gondwana Glaciation (Berner, 2001). In an effort to uncover the factors that contributed to widespread black shale deposition, Late Devonian black shales of the eastern US have undergone extensive study from multiple perspectives, and the state of water column oxygenation has been an issue of ongoing debate (e.g. Sageman et al., 2003; Schieber, 1998, 2003; Rimmer, 2004; Algeo, 2004). For given intervals of this black shale succession, interpretations can range from dysoxic to stratified anoxic or even euxinic (anoxic–sulfidic) bottom waters (e.g. Sageman et al., 2003; Kepferle, 1993; Werne et al., 2002). Because benthic foraminifera require at least some oxygen in order to persist at the seafloor (Bernhard and Reimers, 1991; Bernhard et al., 2003), finding them to be widespread in Late Devonian black shales of the eastern US indicates that extended time periods of stratified anoxic or euxinic bottom waters can be eliminated as factors that contributed to massive carbon burial in these strata. Examination of samples from other geologically significant black shale intervals has revealed remains of agglutinated benthic foraminifera as well, and indicates a need for re-examining the global black shale record.

2. Methods and materials

More than one thousand thin sections from the Appalachian and Illinois Basins of the eastern US (Fig. 1 and Table 1) were examined. This comprehensive data set spans the entire Late Devonian (Frasnian and Famennian) time interval and include all of the regionally extensive black shale units. The slightly older Oatka Creek Shale (Givetian, New York) is included because it is cited as an example of a "euxinic" black shale (Sageman et al., 2003; Werne et al., 2002).

Polished thin sections for this study were prepared by a commercial lab, Petrographic International, in Choiceland, Saskatchewan. Initial screening of thin sections was done with a petrographic microscope (Zeiss Photo III) in transmitted and reflected light. Petrographic microscope images shown here were acquired with a Pixera Pro 600ES digital camera with 5.8 megapixel resolution. A subset of these samples was then examined by scanned color cathodoluminescence in order to confirm the agglutinated character of features identified as agglutinated foraminifera. The used instrumentation was a FEI Quanta FEG 400 ESEM equipped with an energy dispersive X-ray microanalysis (EDS) system and a GATAN Chroma CL cathodoluminescence (CL) detector. High resolution CL scans (4000×4000 pixels, 1000 µs beam dwell time) were run at 10 kV with a narrow lens aperture (aperture 4), and spot size 5. The thin

E-mail address: jschiebe@indiana.edu.

0031-0182/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.palaeo.2008.10.027

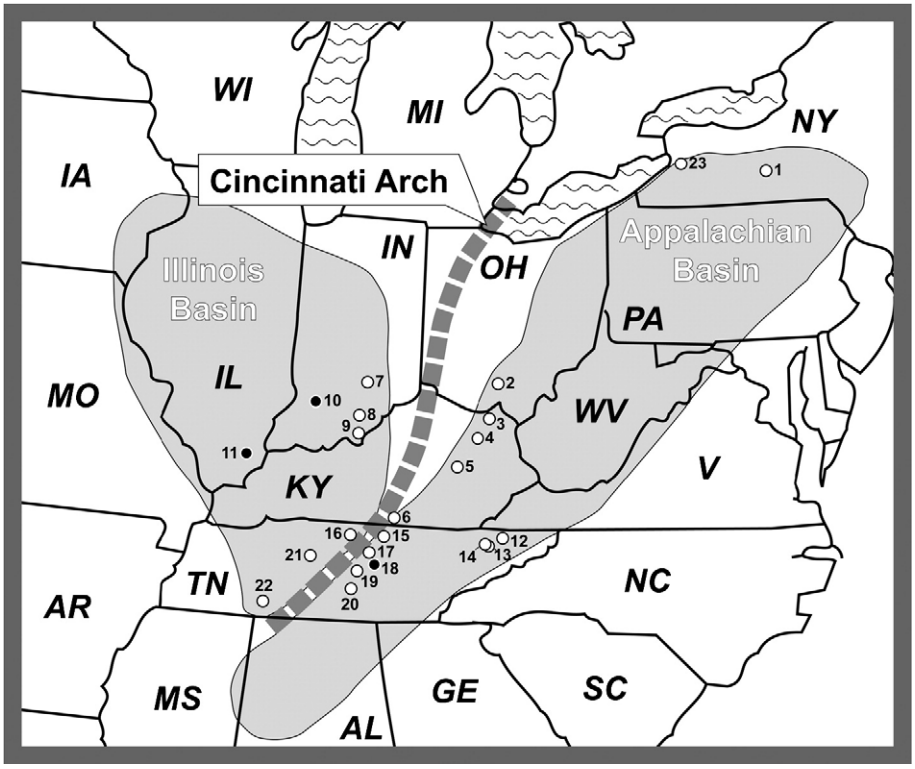

Fig. 1. Overview map of study area in the eastern U.S. States are marked by their outlines and the postal state identifier. The numbers next to sample localities (circles) refer to the location list in Table 1. Full circles (black with white rim) indicate localities where closely spaced samples were examined over the entire stratigraphic thickness. The Illinois and Appalachian Basins are outlined with shading. The dashed line marks the Cincinnati Arch, a positive element that was intermittently flooded during the Late Devonian.

sections were carbon coated and the observations were made under high vacuum. Working conditions for SEM backscatter imaging (BSE) were 10 kV, high vacuum, aperture 4, and spot size 3.

3. Identifying agglutinated foraminifera

Modern muds from the Santa Barbara Basin (offshore California) and the Guaymas Basin (Gulf of California) contain agglutinated benthic foraminifera with well developed grain selectivity (Fig. 2). These foraminifera first accumulate random grains, then incorporate desired grains into new chambers, and finally leave behind the rejects as a "detritic heap" (Pike and Kemp, 1996). Grains are bound by an organic cement, and there is clear preference for fine-grained quartz silt. During burial and compaction their tests collapse, resulting in lenticular bodies of fine quartz grains (some hundred microns long, some tens of microns thick). Internal sutures may be preserved as a

Table 1
Sampled localities

#	Location	Unit	Age	Type
1	South Crosby, Yates Cty., NY	Sonyea Group	Lower Frasnian	Outcrop
2	Tener Mountain, Adams Cty., OH	Ohio Shale and Cleveland Shale	Famennian	Outcrop
3	KEP-3, Adams Cty., KY	Ohio Shale and Cleveland Shale	Famennian	KGS drill core
4	Morehead, Rowan Cty., KY	Ohio Shale and Cleveland Shale	Famennian	Outcrop
5	Irvine, Estill Cty., KY	Ohio Shale and Cleveland Shale	Famennian	Outcrop
6	Burkesville, Cumberland Cty., KY	Chattanooga Shale, Gassaway Member	Famennian	Outcrop
7	Core 763, Bartholomew Cty., IN	New Albany Shale	Frasnian and Famennian	IGS drill core
8	Humphrey #1, Lawrence Cty., IN	New Albany Shale	Frasnian and Famennian	UPR drill core
9	Wiseman #1, Harrison Cty., IN	New Albany Shale	Frasnian and Famennian	UPR drill core
10	Core 873, Daviess Cty., IN	New Albany Shale	Frasnian and Famennian	IGS drill core
11	Core 26376, Saline Cty., IL	New Albany Shale	Frasnian and Famennian	ILGS drill core
12	Eidson, Hawkins Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
13	Rock Haven, Grainger Cty., TN	Brallier Formation	Frasnian and Famennian	Outcrop
14	Thorn Hill, Grainger Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
15	Celina, Clay Cty., TN	Chattanooga Shale, Gassaway Member	Famennian	Outcrop
16	Westmoreland, Sumner Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
17	Chestnut Mound, Smith Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
18	Hurricane Bridge, DeKalb Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
19	Woodbury, Cannon Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
20	Noah, Coffee Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
21	Pegram, Cheatham Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
22	Olive Hill, Hardin Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
23	Lancaster, Erie Cty., NY	Oatka Creek Shale	Givetian	Outcrop

KGS = Kentucky Geol. Surv.; IGS = Indiana Geol. Surv.; ILGS = Illinois Geol. Surv.; UPR = Union Pacific Resources; NY = New York; OH = Ohio; KY = Kentucky, IL = Illinois; IN = Indiana; TN = Tennessee.