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Research paper

Hot shale in an ice world: Paleoceanographic evolution of the northern Gondwana margin during the early Paleozoic (Tanezzuft Formation, Tunisia)

G. Gambacorta [a, *], V. Caronni [a], E. Antonielli [b], E. Previde Massara [a], A. Riva [a], P. Scotti [a], E. Trincianti [a], E. Erba [c]

[a] *ENI S.p.A. Upstream and Technical Services, 20097 San Donato Milanese, MI, Italy*
[b] *ENI Tunisia BV, 1053 Tunis, Tunisia*
[c] *Dipartimento di Scienze della Terra "A. Desio", Università di Milano, Via Mangiagalli 34, Milan 20133, Italy*

A R T I C L E I N F O

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A B S T R A C T

The Tanezzuft Formation deposited in marine periglacial conditions on the northern Gondwana margin during the end of the "ice-house" climate that characterized the lowermost Silurian. The basal part of this sedimentary sequence is characterized by organic-rich facies with locally very high measured Total Organic Carbon (TOC) content up to values greater than 20%. While deposition of organic-rich sediments during greenhouse time interval is well known, deposition of black shales during ice-house conditions is poorly documented. The extraordinary paleoceanographic conditions that led to the accumulation and preservation of enormous amounts of organic matter in periglacial settings, makes this formation an atypical example of black shales deposition.

The study area is situated on the North African Platform in southern Tunisia, on the northern flank of the Ghadames Basin. Petrophysical logs, biostratigraphic, organic- and inorganic-geochemical data from nine wells, are here integrated with the aim of reconstructing the depositional history of the Tanezzuft Formation and the role played by organic matter production, preservation and dilution through time. Data indicate that dilution – that is, depositional style and framework – had an important control on lateral and vertical distribution of the C organic-rich facies. TOC and Hydrogen Index (HI) maxima are found in correspondence of the main transgressive phases, with repetitive stacking patterns strongly associated with source rock properties. Organic matter production, as observed by detailed palynofacies analysis, was mainly marine in nature, with important contribution by Amorphous Organic Matter, Leiosphaeridia/Tasmanaceae and minor amounts of graptolites fragments. Geochemical data indicate that the organic-richest interval ("Hot Shale") of the Tanezzuft Formation deposited under severe anoxic conditions that resulted in enhanced organic matter preservation at the sea-floor. OF-Mod 3D, an organic facies modelling software tool (by SINTEF), is used in order to reconstruct and quantify the peculiar processes that controlled the exceptional accumulation of organic matter at the time of deposition. Modelling results indicate that water stratification was the most plausible process that drove organic-matter sedimentation under mesotrophic conditions. Density stratification was probably controlled by the deglaciation phase after the Hirnantian glaciation and/or by the flooded complex basin physiography that induced an inefficient circulation of the water masses. The complete recovery from these extreme paleoceanographic conditions implied progressive processes that took several hundred thousand years.

1. Introduction

The Early Paleozoic Icehouse (EPI) was an approximately 30 million year interval comprising a series of glacial maxima (Page et al., 2007) that occurred from the Late Ordovician (Katian Stage) through to the Middle Silurian, during a period of high atmospheric

* Corresponding author.
E-mail address: gabriele.gambacorta@eni.com (G. Gambacorta).

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pCO_2 (Royer, 2006). The EPI had its acme during the so called Hirnantian glaciation (Brenchley et al., 1994; Le Heron et al., 2009). Even if there is very little sedimentary evidence of glacial conditions during the Early Silurian (Azmy et al., 1998), data indicate multiple episodes of glaciation and deglaciation, with only partial ice-sheet retreat, that persisted throughout much of the Llandovery Period (Finnegan et al., 2011). The end of the EPI during the Early Wenlock (Cramer and Saltzman, 2005, 2007) marked the beginning of a substantial change in planet's climatic system with a shift to more stable greenhouse condition.

While widespread deposition of C organic-rich sediments during greenhouse time interval is well documented (e.g. Takashima et al., 2006), deposition of black shales during ice-house conditions is poorly known (Page et al., 2007). The boundary between the Ordovician and Silurian ice-house intervals is marked by repetitive periods of anoxia, interspersed with normal oxic conditions. Black shales appear to have become much more widespread in the earliest Rhuddanian than they were in the Late Katian or the mid-Hirnantian (Melchin et al., 2013) (Fig. 1). Sediments showing evidence of deposition under anoxic conditions occur at all paleolatitudes in a very wide range of paleogeographic settings (Melchin et al., 2013). Available data suggest that onset of anoxic conditions took place in Late Hirnantian time, approximately coincident with the major phase of glacial retreat (Page et al., 2007; Moreau, 2011; Melchin et al., 2013). These data also suggest that in many parts of the world, anoxia persisted, either intermittently or continuously, through much of the Rhuddanian, and even into mid-Aeronian time (Luning et al., 2000; Melchin et al., 2013). Thus, based on the first-order pattern of occurrences of black shales, the latest Hirnantian–Rhuddanian interval appears globally to represent a time of much more widely distributed dysoxia-anoxia both at low and high-latitudes in both deep-shelf (below the pycnocline) and basinal settings (Melchin et al., 2013).

The Tanezzuft Formation (Fm.) in southern Tunisia (Ghadames Basin), deposited in the North Gondwanan margin, is a remarkable example of widespread deposition and preservation of organic matter at high-latitudes during the peculiar paleoceanographic settings that characterized the Landovery time interval. This area, positioned in the sub-polar region at approximately 60°S of latitude (Caputo and Crowell, 1985; Scotese and Barrett, 1990; Dalziel, 1997; Mac Niocaill et al., 1997; Smith, 1997; Grunow, 1999; Scotese et al., 1999; Cocks and Torsvik, 2002; Torsvik and Cocks, 2011), was reasonably sensitive to climate variations and major environmental changes, thus representing a key-area for a better comprehension of the processes that controlled the exceptional accumulation and preservation of organic matter.

The main objective of the present work is the assessment of the main regional depositional processes that determined the

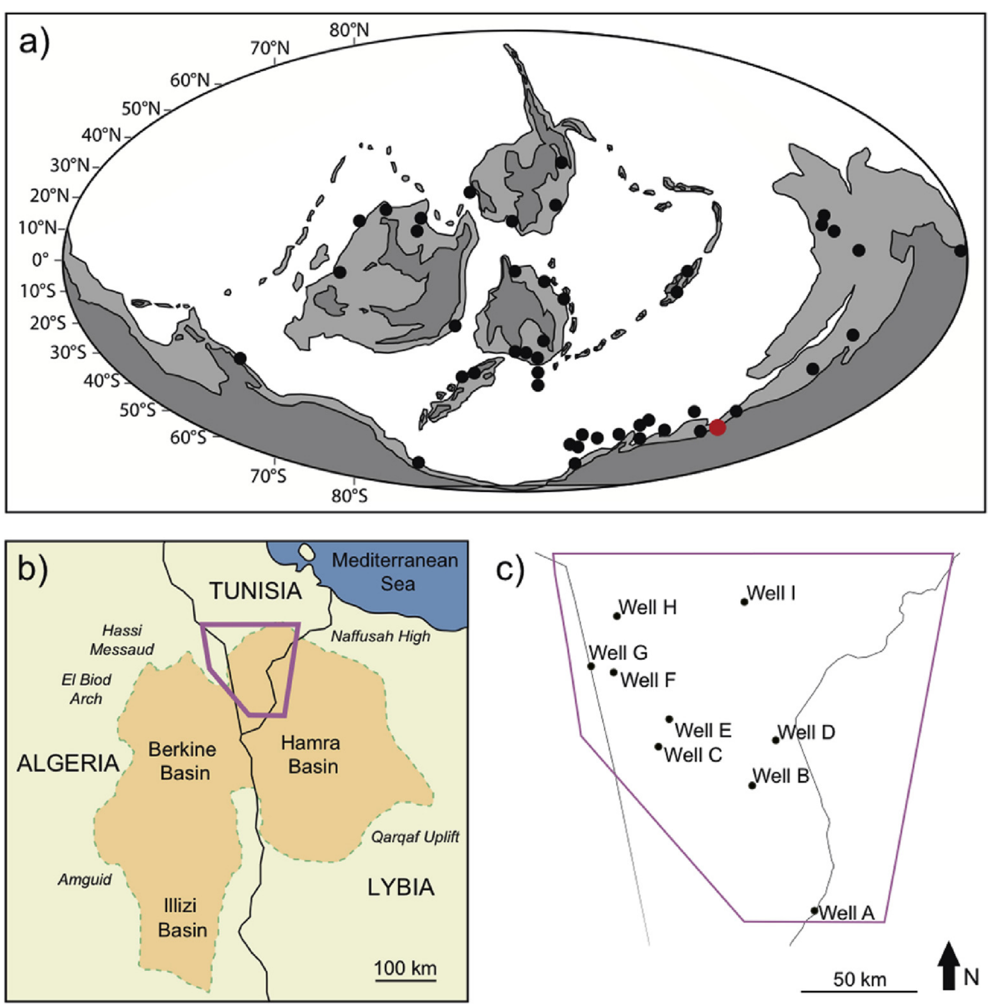

Fig. 1. a) Mollweide paleogeographic map in shows the paleo-location of study area (red dot) at the time of deposition of Tanezzuft Hot Shale, and (black dots) distribution of localities where black shales of the same age have been documented (modified after Melchin et al., 2013). b) and c) Study area location and well distribution. Major geographic lineaments are redrawn from Soua, 2014.