International Journal of Coal Geology 188 (2018) 64–78

Contents lists available at ScienceDirect

International Journal of Coal Geology

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

Application of Palynomorph Darkness Index (PDI) to assess the thermal maturity of palynomorphs: A case study from North Africa

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ARTICLE INFO

Keywords:
Organic matter
Thermal maturity
Silurian
Devonian
Palynomorph Darkness Index
North Africa

ABSTRACT

This study focuses on the thermal maturity assessment of Silurian-Devonian sediments from the Ghadamis Basin, North Africa, comparing optical and geochemical analyses of palynomorphs. In southern Tunisia, the investigated subsurface cored section comprises the Argiles Principales Formation of Silurian age. In Libya, the succession studied covers the Awaynat Wanin III and IV formations, assigned to the Late Devonian (Frasnian-Famennian).

Geochemical approaches used to reconstruct thermal alteration of sediments necessitate advanced, relatively expensive analytical techniques. In this study, the effectiveness of the less costly, relatively simple approaches of visually assessing palynomorph colour to determine thermal alteration (i.e., SCI: Spore Colour Index, TAI: Thermal Alteration Index and PDI: Palynomorph Darkness Index) was evaluated.

SCI and TAI are qualitative methods, strictly related to the operator's perception, which use ten and five point scales respectively, to characterize colour in terms of illustrated specimens and/or descriptions. In contrast, PDI is obtained from the measurement of the red, green and blue (RGB) intensities of light transmitted through palynomorphs, using standard optical microscopes and digital cameras.

The palynomorph-based thermal alteration estimates were compared to Rock-Eval pyrolysis data from the same samples. This calibration showed a linear relationship between these quantitative parameters and PDI. These results show that PDI is more reliable than the SCI and TAI methods.

1. Introduction

It is well known that palynomorphs can be used successfully for a wide range of geological investigations other than biostratigraphy, including sediment provenance analysis (e.g., Vecoli and Samuelsson, 2001), structural geology (e.g. Delcaillau et al., 1998; Dorning, 1986), geo-thermometry (e.g. Pross et al., 2007) and hydrocarbon source rock potential (e.g. Jiang et al., 2016). Sedimentary organic matter (OM) is known for its high sensitivity to thermal evolution. Palynomorphs (e.g. sporomorphs and acritarchs) are composed of resistant organic polymers, the exact molecular structure of which remains the subject of debate; an important characteristic of these polymers is the internal reordering of their molecular structure resulting from processes acting during burial (depth and duration, geothermal flux, fluid geochemistry). In many palynomorphs, these processes result in colour alteration that is directly related to the maximum temperature attained. Nonetheless, post-depositional oxidation due to weathering can not only corrode or even destroy palynomorphs but can also lighten their colour (e.g. Traverse, 2008 and references therein). The characteristic of palynomorphs to change colour with increasing temperature has enabled the development of powerful tools for identifying the thermal history of sedimentary basins (e.g., Batten, 1996; Marshall, 1991; Smith, 1983; Gray and Boucot, 1975). In order to evaluate the thermal maturity of sedimentary OM, several optical, physical and chemical

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https://doi.org/10.1016/j.coal.2018.02.001
Received 30 November 2017; Received in revised form 24 January 2018; Accepted 2 February 2018
Available online 06 February 2018
0166-5162/

maturity methods have been developed (Hartkopf-Fröder et al., 2015 and references therein). Thermal maturity is generally estimated using organic geochemistry (e.g. Rock-Eval pyrolysis; etc.) and optical methods (e.g. Thermal Alteration Index, Spore Colour Index, Acritarch Alteration Index, Palynomorph Darkness Index, Vitrinite and Chitinozoan Reflectances, etc.). Rock-Eval pyrolysis provides different information on the organic content, such as the petroleum potential of a rock, the nature of the kerogen and T_{max}, which is defined as the pyrolysis temperature at which the maximum amount of hydrocarbon is released by kerogen (Espitalié et al., 1986). As a general rule, T_{max} increases linearly with increasing maturity of the OM.

Organic optical methods such as the Thermal Alteration Index (TAI; Staplin, 1969), Spore Color Index (SCI; Smith, 1983), Acritarch Alteration Index (AAI; Williams et al., 1998; Legall et al., 1981) are based on the sensitivity of palynomorph colour to evolve progressively in response to increasing temperature in the lower range of thermal maturity (Marshall, 1991). These approaches are based on the visual inspection of a selected class of palynomorphs to determine their alteration index that can then be correlated with other indicators such as vitrinite reflectance. The estimation of thermal maturity based on optical investigation of microfossils is also relatively inexpensive. Geochemical methods have the main advantage of being independent from the operator's colour perception in contrast to the qualitative TAI, SCI and similar methods. That said, some organic geochemical methods are less reliable in rocks with scarce OM and need specialized and relatively expensive analytical equipment. Recently, Goodhue and Clayton (2010) proposed a new quantitative method to establish the thermal maturity of OM: the Palynomorph Darkness Index (PDI). This is a relatively simple method that utilizes a transmitted light microscope with digital imaging capacity and software capable of simple image analysis. In this study, we applied this method to samples from two subsurface sections in the Ghadamis Basin in southern Tunisia and western Libya of Silurian and Devonian age respectively. PDI values were calibrated against a variety of other thermal maturity indicators in order to evaluate the PDI as a method that can provide a rapid and inexpensive means of estimating thermal maturity and can be deployed during routine palynostratigraphic investigations in thermal history studies of sedimentary basins.

2. Geological setting

The studied subsurface material was obtained from two boreholes, one in southern Tunisia (Tt-1 borehole), and one in western Libya (D1-26 borehole). During Silurian-Devonian time, the study area occupied the depocentre of the Ghadamis Basin, covering an area of about 200,000 km^2 (Fig. 1). This is now an intracratonic depression containing important hydrocarbon plays. To the north and east, the Ghadamis Basin is bounded by the Talemzane Arch (Dahar-Naffusah High) and the Qarqaf Uplift, respectively. The western margin of the basin is marked by the prominent Amguid-El Biod High, a highly faulted uplift trend. To the south, the Ghadamis Basin is separated from the neighbouring Illizi Basin by a series of highs of lower relief. All of these structural features have complex histories, originating during the late Precambrian Pan African orogeny and undergoing repeated reactivation during the Phanerozoic. The sedimentary succession of the Ghadamis Basin ranges in age from Palaeozoic to Cenozoic. It attains a maximum thickness of 3600 m and consists of alternating transgressive and regressive marine sandstone, shales, siltstones and locally limestones, and is represented by the Mamuniyat, Tanezzuft, Acacus, Tadrart, Ouan Kasa, Awaynat Wanin, Tahara and Mrar formations (Acheche et al., 2001).

3. Lithostratigraphy

3.1. Tt-1 borehole

The studied stratigraphic interval from −1286.9 m to −1240.5 m, belongs to the “Argiles Principales” Formation, attributed to the Rhuddanian-Ludfordian time interval (Fig. 2; Vecoli et al., 2009; Jaeger et al., 1975). The basal part of the formation consists of sandstones and quartzites with interbedded shale layers passing to dark grey to black shales and marls, with rare limestone/dolostone intercalations. The upper part is characterized by a monotonous succession of dark grey silty shales. From bottom to top, graptolites of the *vesiculosus* and of the *murchisoni* and *rigidus* zones indicate a Rhuddanian and Sheinwoodian age, respectively. The *lundgreni* graptolite Zone of Homerian age, lies near -1273 m to −1270.5 m. The overlaying interval includes the *vulgaris* graptolite Zone of late Wenlock to lower Ludlow age (Jaeger et al., 1975). The uppermost interval (from −1247.9 m), yielded miospores and chitinozoans of late Ludfordian age (Vecoli et al., 2009). The Silurian sequence ends at a major erosional surface, above which Lopingian deposits were documented (Jaeger et al., 1975).

3.2. D1-26 borehole

The D1-26 borehole penetrated the Acacus Fm. (Silurian) to Garian Fm. (Turonian). In the present study, core samples from the Devonian Awaynat Wanin Group were analysed (Fig. 2). In its Awaynat Wanin

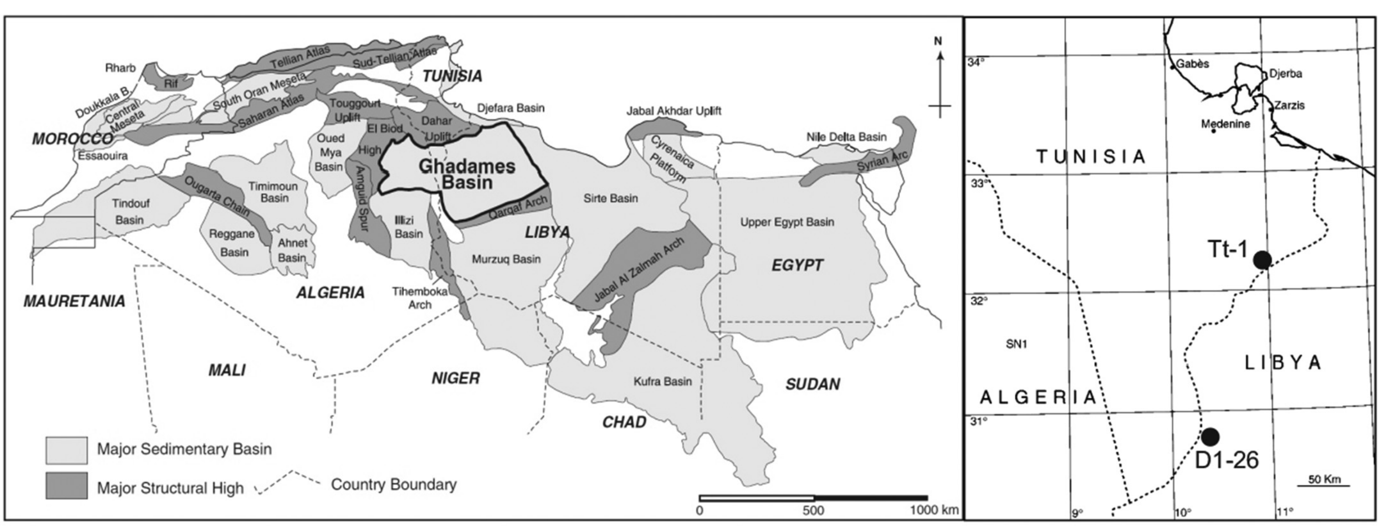

Fig. 1. Location map of the boreholes studied in the Ghadamis Basin (from Underdown et al. (2007) with reference).