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Research paper

Overcoming pitfalls of vitrinite reflectance measurements in the assessment of thermal maturity: the case history of the lower Congo basin

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A B S T R A C T

Vitrinite reflectance has been always considered the most reliable thermal maturity indicator in sedimentary basins. Nevertheless the reliability of vitrinite reflectance measurements can be affected by many external factors that change from basin to basin (e.g. organic facies, temperature and pressure conditions) leading to wide uncertainties in thermal modelling calibration and thus in the evaluation of timing and amount of hydrocarbons generation.

We demonstrate that in case of vitrinite suppression and/or retardation in siliciclastic successions, the classical Sweeney and Burnham kinetics do not match the actual thermal evolution of the basin. In these cases, thermal evolution can be successfully modelled using a complementary approach based on smectite illitization kinetics or more appropriate kinetics (e.g., PresRo^{TM} and T-P-Ro) to evaluate the effect of pressure on organic matter maturation where pressure data are available. This approach was applied in the Lower Congo Basin where 32 cuttings from a 5 km-deep well drilled in the Upper Oligocene-Miocene Malembo formation have been analysed to derive organic and inorganic constraints to model the basin thermal evolution.

Vitrinite and bitumen reflectance measurements show values between 0.3 and 1.0% along the well, whilst the illite content of mixed layer I-S ranges between 35 and 88%, passing from R0 to R1 to R3 stacking order with increasing depth. Present-day temperature distribution through the well indicates a geothermal gradient of about 40 °C/km and measured pressures show an overpressured interval between 3 and 4 km depth.

Retardation and suppression phenomena affected vitrinite reflectance in this interval but did not influence smectite illitization. The comparison between thermal maturity scenarios constrained by organic and inorganic thermal indicators shows differences in the calculation of the depth of the onset of hydrocarbon generation that is overestimated of about 500 m in the Lower Miocene interval when only suppressed/retarded vitrinite reflectance values are used to calibrate models.

1. Introduction

The reliable assessment of thermal maturity of sedimentary successions is a key topic for the quantitative evaluation of hydrocarbon (HC) generation/expulsion and more in general for basin analysis studies (Allen and Allen, 2013). In particular, in HC exploration, uncertainties in thermal maturity assessment can affect the calibration of thermal models and therefore influence decisions on the development of HC prospects.

In general, vitrinite reflectance (R_o%) has been proven to be the most reliable technique in evaluating the thermal maturity of sediments as it is highly sensitive to temperature and is not affected by retrograde metamorphism (Teichmüller, 1987). However, several limitations arise when sediments are devoid of vitrinite macerals (e.g., Lower Paleozoic rocks; Caricchi et al., 2016) and/or are poor in organic matter content.

In addition, high hydrogen contents in kerogen and aliphatic-rich vitrinite may suppress reflectance measurements (Carr,

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2000; Petersen and Rosenberg, 1998; Price and Barker, 1985) until the hydrogen is completely removed from the kerogen structure (Carr, 2000). Suppression phenomena are widely reported in the North Sea (Petersen and Rosenberg, 1998; Senftle and Landis, 1991), in the Carnarvon Basin in Western Australia (Wilkins et al., 1995) and in the Malay Basin in the Vietnam offshore (Petersen et al., 2009).

Moreover, other pitfalls in vitrinite reflectance measurements can occur in geological environments characterized by rapid sedimentation, where overpressure is common and can retard organic matter maturation (Carr, 1999; Dalla Torre et al., 1997; McTavish, 1978). Retardation phenomena relate to a thermochemical reduction in reaction rate resulting from the effects of overpressure in a sedimentary basin. Carr (1999) and Uguna et al. (2012, 2014) pointed out that overpressure appears to restrict the release of volatiles from vitrinite structure. Thereby vitrinite retains lower reflectance values than those expected at the same temperature under hydrostatic pressure. Retardation processes due to overpressure have been extensively recognized in the North Sea, in the Yinggehai Basin and in the Niger paleodelta (MacTavish, 1978, 1998; Hao et al., 1996; 2007).

In these cases, the use of other thermal maturity indicators derived from the analysis of the organic (e.g., TAI, T_{max}) and/or the inorganic fraction of sediments (e.g., fluid inclusions, apatite fission tracks and mixed layer illite-smectite; e.g., Aldega et al., 2014; Cantarelli et al., 2013; Caricchi et al., 2015a, b; Di Paolo et al., 2014) may overcome these issues.

In this work we unravel, using a multimethod approach, the thermal history of the Malembo Fm in the Lower Congo Basin which is one of the worldwide main targets for deepwater oil exploration (Anderson et al., 2000; Anka et al., 2009; Gay et al., 2004; Uenzelmann-Neben, 1998; Valle et al., 2001). A vitrinite reflectance profile through a 5 km deep well presents an unusual trend with respect to the expected paleo-geothermal gradient since Oligocene times, as also reported by Anka et al. (2013) in the same stratigraphic interval.

For this reason we combined mixed layer illite-smectite (I-S) and vitrinite- and bitumen-reflectance (R_o% and R_{oeq}%) to model the thermal evolution of the sedimentary succession by using different kinetic approaches (Carr, 1999; Cuadros and Linares, 1996; Sweeney and Burnham 1990; Zou and Peng, 2001). We suggest that in case of retardation and/or suppression, the classical Sweeney and Burnham (1990) vitrinite reflectance model, is not adequate for assessing thermal history. Thus, we show how to overcome this issue using an alternative approach based on smectite illitization whose maturation pattern does not seem to be retarded by overpressure (Colten-Bradley, 1987). In addition, we suggest the use of kerogen maturation kinetic equations which take into account the effect of overpressure in order to correctly assess hydrocarbon generation/expulsion windows.

2. Geological setting

2.1. Western Africa offshore: from rifting to passive margin evolution

The Western African continental margin formed as a result of Gondwana break-up in the early Cretaceous (Brice et al., 1982; Standlee et al., 1992). First continental rifting occurred at the end of the Late Jurassic-Neocomian (~140–150 My) (Binks and Fairhead, 1992; Davison, 1999; Dupré et al., 2011) whereas crustal separation and onset of oceanic spreading took place ~133 My ago (Dupré et al., 2011) and remained active until the Late Aptian (Brice et al., 1982; Dupré et al., 2011; Karner et al., 1997; Lavier et al., 2001). Various deep underfilled lacustrine basins formed during rifting in Early Cretaceous times (Anderson et al., 2000). Continental sedimentation went on until the Aptian when it evolved to shallow marine conditions driven by thermal subsidence of the passive margin (Anderson et al., 2000; Séranne, 1999; Valle et al., 2001).

Currently the basins forming the western Africa Passive margin are: the Gabon, the Lower Congo and the Kwanza Basins (Fig. 1).

2.2. Stratigraphic evolution of the lower Congo basin

The Lower Congo Basin is one of the sub-basins developed on thinned continental crust along the Western Africa passive margin. It is located between the Gabon Basin to the north and the Kwanza Basin to the south (Fig. 1).

The sedimentary infill is organised into three megasequences (Ala and Selley, 1997; Brice et al., 1982; Valle et al., 2001): 1) the "syn-rift megasequence" (Late Jurassic-Early Cretaceous), 2) the "transitional/early drift megasequence" (Aptian) and 3) the "drift megasequence" (Albian-Holocene).

"Syn-rift" sedimentation in the Early Cretaceous is related to different phases of rifting (de Matos, 1999; Karner and Driscoll, 1999) which led to the generation of deep, underfilled lacustrine basins (pre-salt sediments of the Lucula and Bucomazi formations, Fig. 2).

The end of rifting in the Early Aptian is recorded by a transgressive clastic succession composed of fluvial sandstones and marine shales (Chela formation, Fig. 2) overlain by the evaporitic levels of the Loeme formation (Anka et al., 2009) (Fig. 2). Due to halokinetic movements, the Loeme formation shows large thickness variations, from nearly zero to up to 1000 m along the Congo

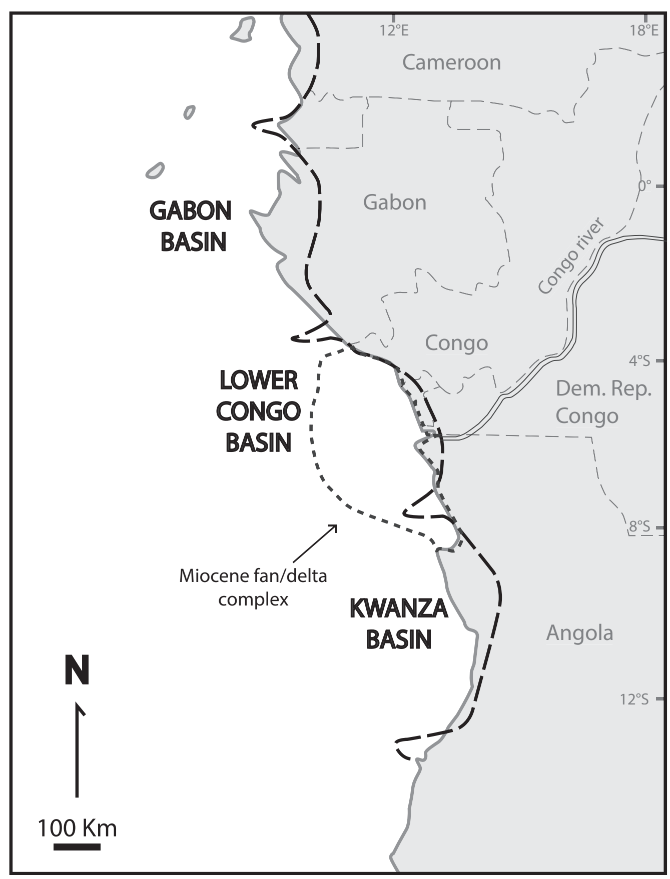

Fig. 1. Simplified map of the basins forming the West African margin and extension of the Miocene fan-delta complex. Redrawn after Anderson et al. (2000).