Total Organic Carbon estimates from wireline logs - Part #1
by Andrew Green

Unconventional exploration is providing the discipline of organic geochemistry with an unprecedented opportunity to investigate, analyse and further our knowledge of petroleum source rocks. Over the past decade we have greatly advanced our understanding of shale composition, hydrocarbon generation, expulsion efficiencies and now have a clearer idea of the criteria required in order for a play to be prospective (Jarvie, 2012).

A decisive factor for any producible shale resource system is the quantity of total organic carbon (TOC) present, as it provides an essential indication of the oil and gas generation potential while also forming an important control on retained petroleum volumes (Crain, 2010; Gonzalez *et al*., 2013). However, many authors have indicated that unconventional systems vary compositionally both between different shale systems and also internally within a particular shale system (Passey *et al*., 2010; Crain, 2011) thus making conventional TOC analytical screening programmes ineffective due to a lack of vertical data resolution within a well. Consequently, estimation of TOC from wireline logs is seen as an effective and cost viable approach to counter sampling discontinuity experienced from analysis of core and cutting samples (Zhoa *et al*., 2016).

The utilisation of wireline logs to achieve accurate estimations of TOC and provide a high resolution record of organic carbon variance down hole is neither a new venture nor specific to unconventional petroleum systems. Numerous authors since 1980 have also recognised the benefits of wireline log derived TOC in conventional exploration (Smoker, 1981; Dellenbach *et al*., 1983; Mayer & Nederlof, 1984; Passey *et al*., 1990), noting that estimation of source rock characteristics beyond that achieved from physical sampling is essential for the spatial delineation of depositional environments and appropriate hydrocarbon generation potential; both key inputs for basin modelling.

Many of the approaches proposed to date for estimating TOC from wireline logs, all requiring sample to log calibrations to ensure validation locally, are concisely summarised by Zhoa *et al*. (2016). The published methods can be conveniently separated into two categories:

- TOC derived from a direct empirical relation between a petrophysical curve of choice and analysed core/cuttings data
- TOC derived from the separation resulting from the overlay of two petrophysical curves

The overlay approach to TOC estimation from wireline logs is preferable over a direct calibration as it not only produces a measure of TOC but also, depending on the overlain petrophysical curve pair, will provide a means to distinguish source rocks *vs*. non-source, clay-rich rocks or source rocks *vs*. non-source rocks present in any investigated well. Three overlay methods which are available to the geochemist / petrophysicist are:

- The ΔlogR method published by Passey *et al*. (1990) and amended for thermally mature unconventional shale gas systems in Passey *et al*. (2010). This method sees a porosity curve (primarily acoustic sonic curve [AC]) overlain with the resistivity [RT] curve (ideally the deep RT curve)
- The Jacobi *et al*. (2008) method utilises the density difference between the grain density (measured from the nuclear magnetic resonance [NMR] and bulk density [DEN] curves) and inorganic grain density (measured using geochemical logs [GC]) to estimate TOC

- The Zhao *et al*. (2016) method overlays a derived clay indicator curve with a natural gamma-ray [GR] curve in order to remove the natural clay mineral radioactive signal and leave the residual kerogen-derived GR response for TOC estimation. This is applicable where a source rock's naturally high detectable radiation is perceived to be predominantly derived from clay minerals and kerogen (associated Uranium), as found in marine and certain continental settings

Despite the Jacobi *et al*. (2008) method utilising new technologically advanced equipment and seen as an accurate approach to TOC determination it cannot be employed widely across global basins as the cost involved in running NMR and geochemical log tools is still prohibitive; consequently, they are not routinely run. The other two methods however are more applicable across the industry as they utilise petrophysical curves that are regularly recorded as part of a wireline log suite. The latter method, a new approach to TOC estimation from commonly available logs published by Zhao *et al*. (2016), will be discussed in detail in Part #2 of this article.

TOC - ΔlogR separation method

The ΔlogR separation method is still today the most widely used model for estimating organic richness from well logs. It overlays a porosity curve (commonly the Sonic curve, but the method can also be applied with either a Density or a Neutron curve) and a Resistivity curve in a scaled track (50µs/ft = 1 logarithmic cycle) such that the two curves overlie in a zone of non-source, clay-rich rock close to the organic-rich interval of interest. Separation of the curves (termed ΔlogR), following the establishment of a 'baseline' for the two curves over non-source, clay-rich rocks, results as a consequence of either or both (Fig. 1):

- Source rock organic richness – *i.e.* TOC% (shifting the Sonic curve to higher values)
- Source rock maturation (shifting the Resistivity curve to higher values)

$$\Delta logR = log_{10}(R/R_{base}) + 0.02*(\Delta t- \Delta t_{base}) \qquad (Eq: 1)$$

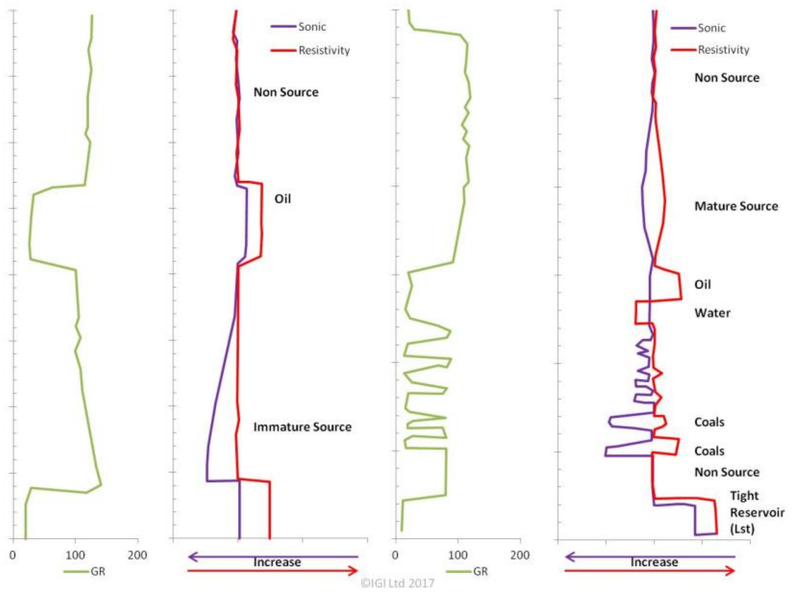

Fig. 1: Cartoon representation of GR and ΔlogR Sonic/Resistivity overlay curve responses to various downhole formation configurations. Adapted from Crain (2010)

ΔlogR is positively correlated to the quantity of TOC given a knowledge or estimate of the thermal maturity. The maturity reference used by Passey *et al*. (1990) was the Level of Organic Metamorphism (LOM) which ranges from <5-12. In practice LOM is derived from a number of measured maturity parameters, most commonly involving vitrinite reflectance or T-max (Fig. 2).

$$TOC= [(\Delta logR)*10^{(2.297-0.1688*LOM)}] \qquad (Eq: 2)$$

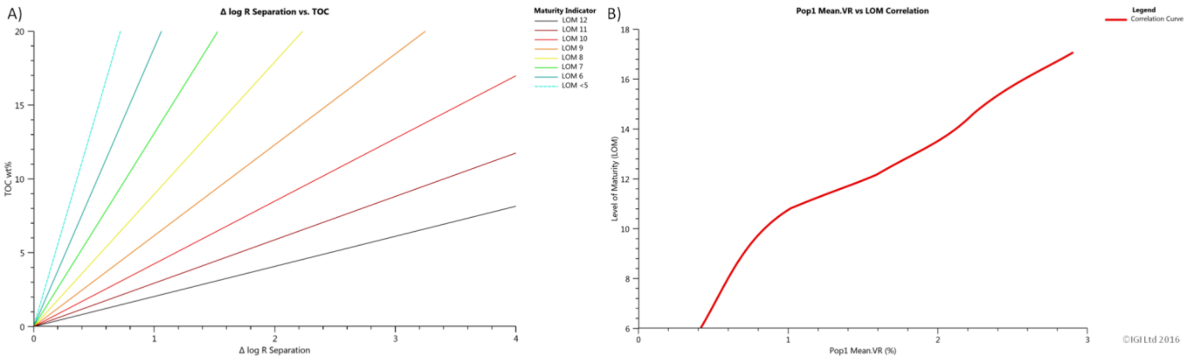

Fig. 2: A) Positive linear relationship between ΔlogR separation *vs*. TOC wt% for a given thermal state (LOM) B) The relationship between LOM and vitrinite reflectance can be determined using a 5th order polynomial relationship. Images adapted from Passey *et al*. (1990) & Crain (2010) respectively.

Despite the widespread applicability of this method there are, as for any petrophysical model, certain assumptions and drawbacks associated with the ΔlogR approach to TOC estimation. These include:

- An assumption that the matrix properties for both the organic-rich source rock and non-source, clay-rich rocks are identical.
- The presence of expandable clays, e.g. smectite with high amounts of associated clay-bound water, produces a reduction in resistivity and consequently an underestimation of TOC content.
- The original calibration of ΔlogR, published in Passey *et al*. (1990), was only for source rocks in the oil maturity window (LOM 6-10.5, %Ro 0.5-0.9). No data were available for rocks in the overmature gas window (LOM >10.5, %Ro >0.9) and so the maturity LOM lines >10.5 (Fig: 2a) were just numerical extrapolations. Passey *et al*. (2010) revisited the ΔlogR *vs*. TOC plot in light of available worldwide shale-gas data and proposed a revised calibration (Fig. 3).
- Zhao *et al*. (2016) provide case studies where despite the widespread application of the ΔlogR method, certain shale gas formations display abnormal resistivity responses which prevent TOC quantification. In the Sichuan Basin (China) for example, organic shales at maturities >2.5%Ro display resistivity values lower than the non-source, clay-rich rocks (opposite to the ΔlogR theory).

In the second part of this article a new practical wireline log overlay approach to TOC estimation will be presented and thought given to its application in comparison to the long established ΔlogR separation method.

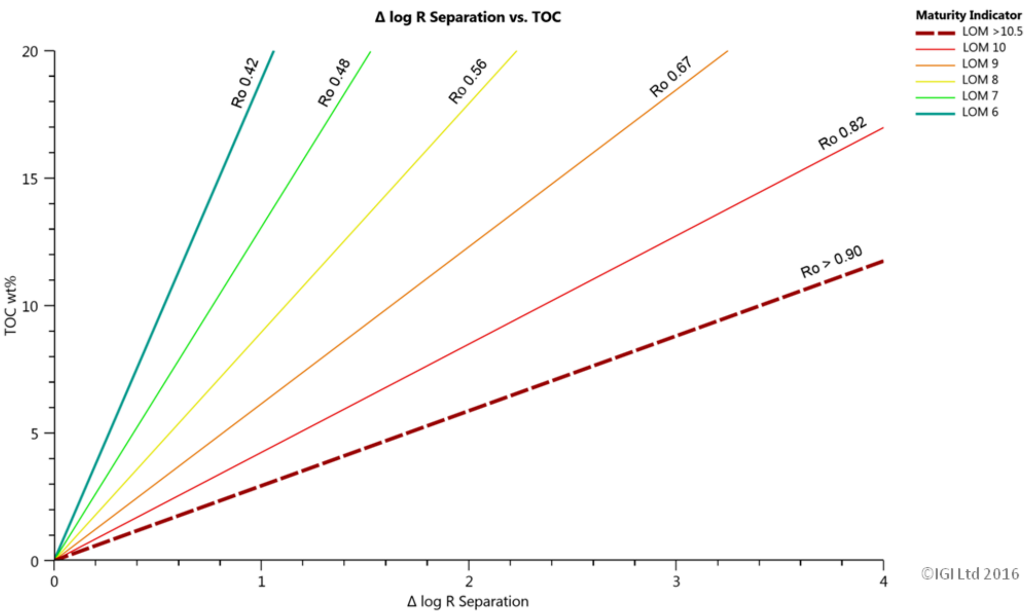

Fig. 3: Revised positive linear relationship plot between ΔlogR separation *vs*. TOC wt% for a given thermal state (LOM / %Ro). The graph, edited in light of data from unconventional shales within the gas window, proposes an upper limit for rocks with LOM>10.5, %Ro >0.90 (Passey *et al*., 2010).

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