Total Organic Carbon estimates from wireline logs - Part #2
by Andrew Green

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[1] vary compositionally both between different shale systems and also internally within a particular shale system (Passey *et al*., 2010; Jarvie, 2012) 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 (Zhao *et al*., 2016).

In part #1 of this investigation into methods associated with estimating TOC from wireline logs, two overlay approaches[2] were presented with TOC derived from the separation resulting from the overlay of two regularly recorded petrophysical curves:

- ΔlogR separation method (the most widely used approach for estimating organic richness)
- Clay Indicator-GR separation method

Overlay methods are noted to present a distinct benefit in contrast to direct empirical relations between a petrophysical curve of choice and analysed TOC core/cuttings data. This is due not only to the TOC value which is derived from the approach but depending on the overlain petrophysical curve pair a distinction is achieved between source rocks *vs*. non-source shales and source rocks *vs*. reservoir rocks (Passey *et al.,* 2010; Zhao *et al*., 2016).

Despite the widespread applicability of the ΔlogR separation method, certain assumptions and drawbacks associated with this approach to TOC estimation do exist. These include:

- An assumption that the matrix properties for both the organic-rich source rock and non-source shales 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 optimised for source rocks in the early to main oil maturity window (LOM 6-10.5, %Ro 0.5-0.9). No data were available for rocks in the late oil and gas windows (LOM >10.5, %Ro >0.9) and so the maturity LOM lines >10.5 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 (see Technical Note Part: 1).
- 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

[1] Despite the increased analytical research which is being conducted on organic-rich shales in connection with unconventional petroleum systems, many of the key observations, *i.e.* internal shale facies and composition, are also applicable to organic-rich shales associated with conventional petroleum systems.
[2] A third overlay method, Jacobi *et al*. (2008), was mentioned but was not discussed in detail as despite utilising new technologically advanced equipment, cost is prohibitive towards routinely running tools such as NMR.

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, which oppose the ΔlogR theory (Fig.1).

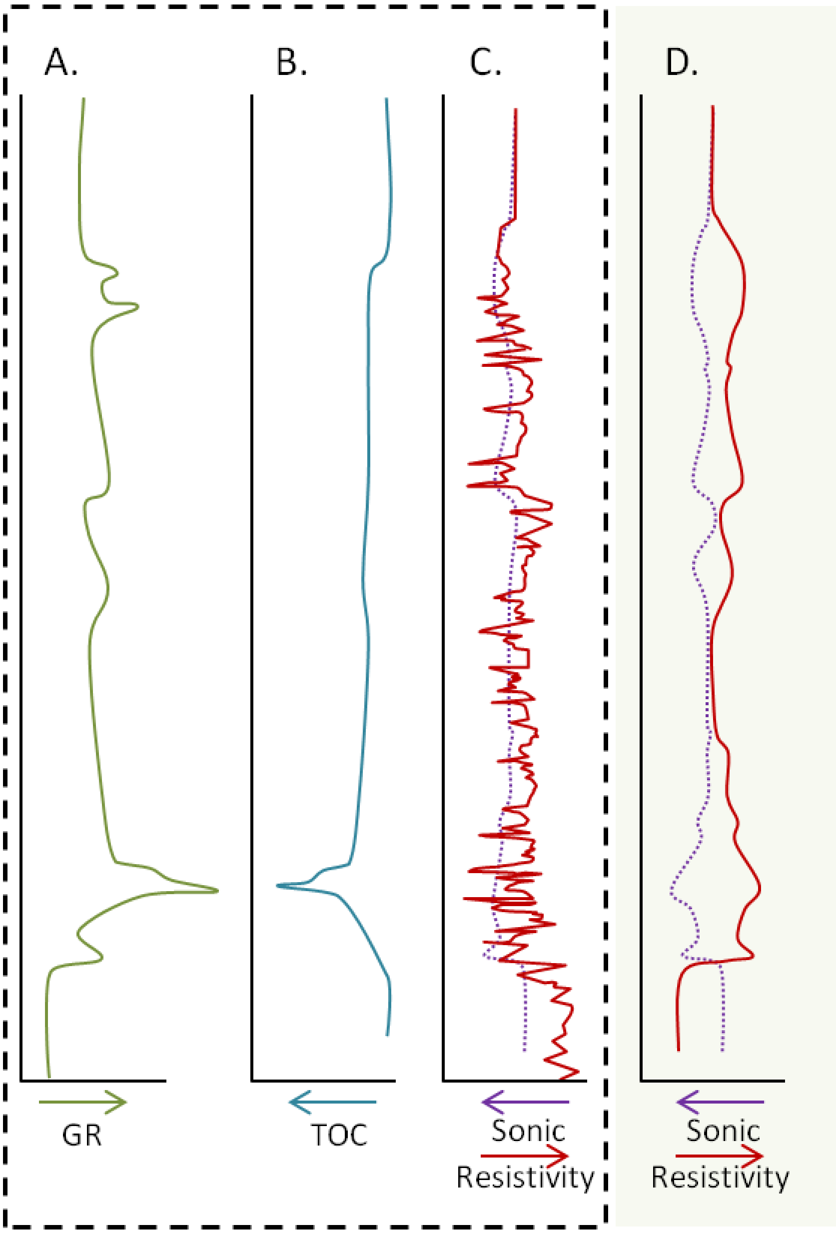

Fig. 1: Track C provides a cartoon representation of the anomalous ΔlogR Sonic/Resistivity overlay response seen in the Sichuan Basin (China) across an organic-rich section (TOC in Track B uses the new Zhao *et al*. (2016) method as described herein). Track D provides an idealised ΔlogR Sonic/Resistivity overlay response expected across the same organic-rich section. Adapted from Zhao *et al*. (2016)

In response to anomalous ΔlogR Sonic/Resistivity overlay responses seen in high maturity shale gas plays of the Sichuan Basin (China), Zhao *et al*. (2016) presents a new log overlay method, aligning 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. Utilising a suite of regularly recorded petrophysical curves this new approach has the potential to be widely applicable and effectively suited not only to highly mature but also low maturity kerogen.

TOC – Clay Indicator-GR separation method

As a method preferentially designed for marine and some continental depositional environments[3], in which shales and mudstones host high natural GR activity, elevated API (American Petroleum Institute units) response values are the combined result of syngenetic uranium absorption by organic matter (Rider, 2006) and natural radiation from clay minerals (Fig.2).

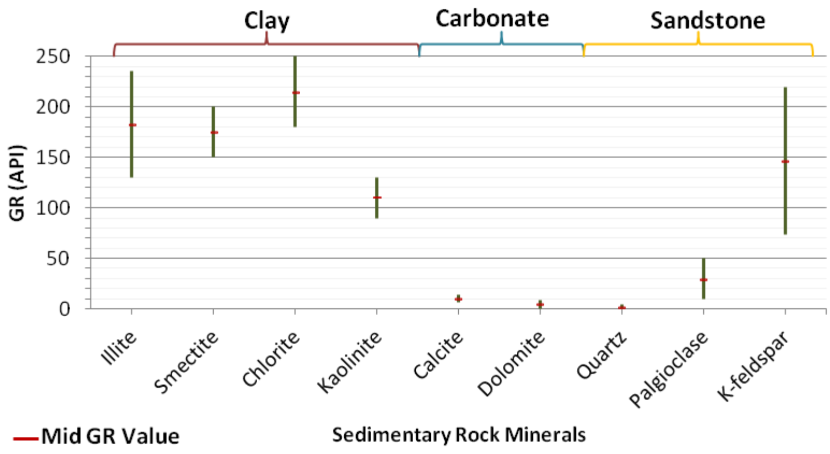

Fig. 2: Typical Gamma Ray (API) values for commonly occurring minerals in sedimentary clay, carbonate and sandstone rocks.

Along with clay minerals which emit high values >100API, potassium feldspar (a common constituent of sandstone) is seen to exhibit high natural radioactive values and so for this method to effectively work source rocks are assumed to contain little or no potassium feldspar.

The **clay indicator (*I_{cl}*)** parameter (Equation. 1), resulting from the difference between the apparent neutron porosity and apparent density porosity, allows for the identification and removal of the clay mineral's radioactive contribution from the GR response. The estimation of TOC is then viable from the residual GR response from the uranium-induced radioactive activity (Zhao *et al*., 2016).

$$I_{cl} = \phi_{Na} - \phi_{Da}{}^{4} \quad (1)$$

$$\phi_{Na} = \phi_{N}/100^{5} \quad (2)$$

$$\phi_{Da} = (\rho_b - \rho_{ma}) / (\rho_f - \rho_{ma})^{6} \quad (3)$$

In reservoir rock and non-source shales devoid of organic matter and consequently uranium, the clay indicator should function similarly to the GR log as all natural radiation is mineral sourced (Fig. 3).

[3] Lacustrine depositional environments are not enriched in uranium ions and thus associated organic matter does not exhibit reliably high GR values and thus use this approach as a source rock indicator (Meyer & Nederlof, 1983).

[4] Resultant **I_{cl}** curve is presented in V/V units

[5] **ϕ_{Na}** is the **apparent neutron porosity** of the limestone calibration in V/V, **ϕ_N** is the CNL log value in porosity units (PU)

[6] **ϕ_{Da}** is the **apparent density porosity** of the limestone calibration in V/V, **ρ_b** is the DEN log value in g/cm^3 , **ρ_{ma}** is the density value of limestone, 2.71g/cm^3 , **ρ_f** is the fluid density value, 1.0 g/cm^3

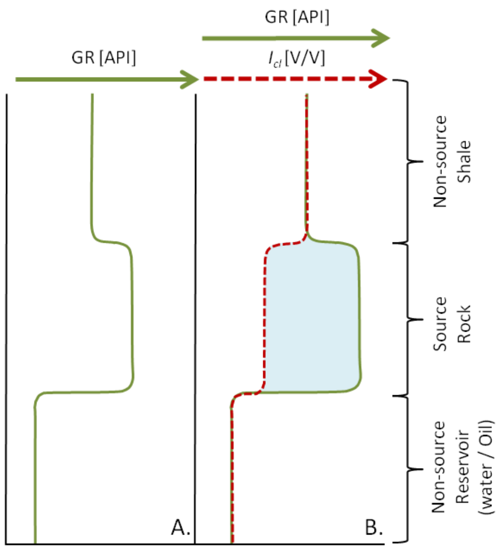

Fig. 3: A cartoon representation of the new Zhao et al. (2016) overlay method, where the Gamma Ray (**GR**) curve is overlain with a scaled Clay indicator (***I_{cl}***) curve. In both non-source shale and reservoir intervals where the entirety of the GR response is the result of mineral-sourced natural radiation, the curves overlay. In organic-rich source rock intervals the curves separate.

Practical application of the Clay Indicator-GR separation TOC method is achieved through the display of the GR and clay indicator curves in the same log track. The scales of the curves are then adjusted to ensure that the curves overlie for non-source shale and reservoir rocks. Any resultant separation which then occurs between the curves down the length of the track is due to the presence of organic matter. The separation between the two curves (**Δd**) is thus relational to kerogen content and once a relationship is established between **Δd** and a calibration core TOC dataset then the TOC of the entire well bore section can be estimated.

$$\Delta d = GR' - I_{cl}' \quad (4)$$

$$GR' = \frac{GR - GR_{Left}}{GR_{Right} - GR_{Left}}\ ^{7} \quad (5)$$

$$I_{cl}' = \frac{I_{cl} - I_{cl_{Left}}}{I_{cl_{Right}} - I_{cl_{Left}}}\ ^{8} \quad (6)$$

$$TOC = a^{*}\Delta d + b\ ^{9} \quad (7)$$

Two limitations of this TOC curve separation technique include 1) the ineffective performance of the clay indicator in reservoir intervals which contain significant amounts of gas due to the effect it has on the neutron measurements[10], and 2) bore hole condition will have an adverse effect on both density and neutron measurements, which will consequently be transmitted through to calculated TOC values.

[7] *GR* is the log value in API gravity, GR_{Left} is the left scale of the GR curve in API gravity, GR_{Right} is the right scale of the GR curve in API gravity.
[8] I_{cl_Left} is the left scale of the clay indicator curve, and I_{cl_Right} is the right scale of the clay indicator I_{cl} curve.
[9] *a* and *b* are the slope and intercept values of the linear relationship created between *Δd* and a calibration core TOC dataset, respectively.
[10] The effect free gas in Non-source reservoirs has on the neutron measurement has not been identified or verified in shale gas reservoirs, despite speculation in the past (Zhao, 2013).

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