

Back to Source Rocks: Part I

RASOUL SORKHABI, Ph.D

The science and analytical techniques to investigate petroleum source rocks have been developed over the past four decades. Understanding the geology and geochemistry of source rocks is crucial to petroleum geoscience and engineering. In Part I of this article, we review the protracted (with hindrances) formation of organic matter in source rocks, involving processes from solar radiation to sea-floor sedimentation.

The petroleum system consists of source rock, migration pathways, reservoir, seal, and trap. Source rocks represent the hydrocarbon kitchen (generation) in a sedimentary basin. The source rock is also the first logical step to assess a petroleum system, for no matter how excellent a reservoir or a trap may be, without an effective source rock there would be no petroleum charge into the basin.

Searching for Good Source Rocks

Although there is evidence for non-organic methane (notably, gas emissions from volcanic eruptions), the majority of petroleum geochemists and geologists rightly regard the hydrocarbons we produce from sedimentary basins to be of organic origin. One line of evidence is oil shale, which contains plenty of

organic matter (kerogen) but since the rocks were never deeply buried, the kerogen is thermally immature, and upon heating ('cracking'), it transforms to simpler hydrocarbon molecules, similar to those found in petroleum reservoirs. Source rock is the mother of all oil and natural gas reserves.

Fine-grained, clay-rich sedimentary rocks including mudstone, shale (platy mudstone), marl (calcareous mudstone), limestone, and coaly rocks (especially for natural gas) are usually considered to be possible source rocks because coarse-grained sediments are too porous and permeable to retain organic matter. Moreover, organic matter tends to adsorb onto mineral surfaces of clay-rich sediments which, being fine-grained, have a larger mineral surface

area per unit of rock volume. Marine environments in which fine-grained mudstone and clay-rich limestone are deposited coincide with the habitat and burial site of plankton biomass (which contribute 90% of organic matter to petroleum source rocks). Indeed, ocean waters, biota and rocks are the largest sink of carbon on Earth.

A 'good' source rock that yields commercial volumes of petroleum must have a high organic content and have compounds of both carbon and hydrogen molecules (otherwise, we end up with coal). It must be thermally mature through burial, have considerable thickness and lateral extent, and should be able to expel the generated oil.

A given shale formation will have different source-rock characteristics

Upper Cretaceous Mancos Shale, Capitol Reef National Park, Utah.



and ranking in various locations in a basin, and needs to be studied in detail.

Source Rocks in E&P

Despite its fundamental importance, the source was the last component of the petroleum system to be investigated scientifically, and petroleum geology textbooks of the 1920s–50s dealt mostly with reservoirs and traps. The first petroleum geochemistry books appeared in the late 1970s, including *Petroleum Formation and Occurrence* by B.P. Tissot and D.H. Welte and *Petroleum Geochemistry and Geology* by John Hunt.

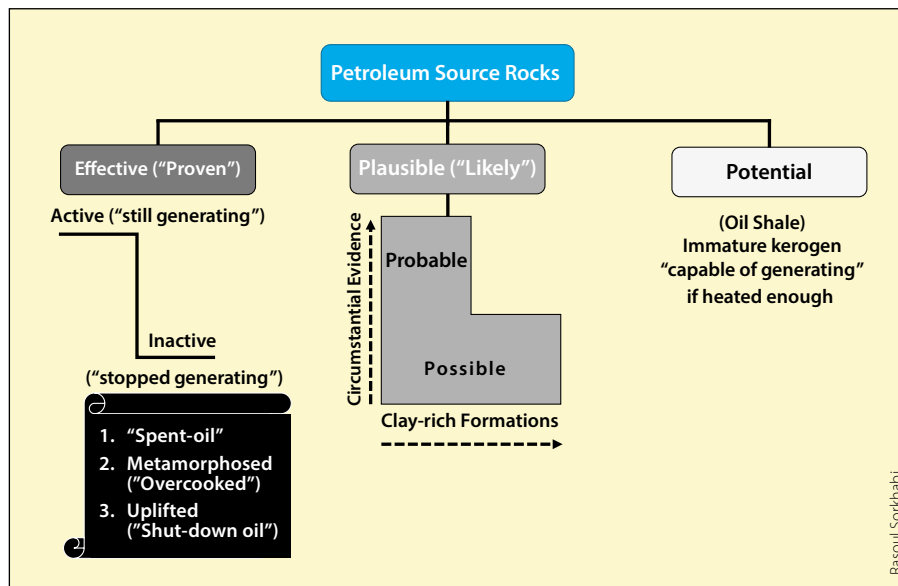
Because source rocks lie in the deeper parts of the basin they are not easily accessible for sampling and analysis. Analytical techniques for source rock geochemistry are also relatively recent: RockEval (pyrolysis) and vitrinite reflectance techniques were developed in the 1970s, and basin modelling software for source rock maturity and petroleum generation appeared in the 1980s.

The history of the petroleum industry since the mid-19th century may be viewed as the rise of four waves in exploration and production: onshore; nearshore and shelf; deepwater; and shale. For most of this history, exploration onshore and nearshore was primarily based on locating seeps and trap structures (so-called ‘wildcatting’). In deepwater basins the source rock is the last layer to be drilled, so we still have little data for deepwater source rocks.

The significance of source rock knowledge in exploiting shale plays should not be underestimated. Even though producing from these low-permeability rocks requires direct drilling, hydraulic fracturing and mapping of fracture sweet spots, at the resource level, the efficiency of shale plays is controlled by their geochemical, mineralogical, depositional and thermal maturity properties.

From Sunlight to Kerogen

Carbon (from Latin *carbo*, charcoal), with atomic number six, is the fourth-most abundant element (0.46% by mass) in the Milky Way galaxy, after hydrogen, 74%, helium, 24% and oxygen, 1.04%. Carbon, like many other elements, was created inside previous



A classification of source rocks based on their probability of performance.

stars in the universe by nucleosynthesis. It constitutes no more than 0.18% of Earth’s crust.

Before oil and gas are generated in the source rock, there is a long pathway for organic matter to be produced, accumulated and preserved in the basin. Organic matter dispersed in sediments is called kerogen (Greek: *keros*, wax, and *gen*, birth), a mixture of complex carbon-based chemical compounds that are insoluble in normal organic solvents because of their high molecular weights. The term kerogen was introduced by the Scottish chemist Alexander Crum Brown in 1906. Note that fresh organic matter in unconsolidated sediments up to 100m deep is not regarded as kerogen.

We often think of solar power as radiation from the sun that directly reaches Earth, but fossil fuels are also solar energy stored in rocks because the sun’s radiation (electromagnetic force) is involved in the production of organic carbon. Fossil fuels are an important component of the carbon cycle on Earth, which describes the interlocking circuits of carbon reservoirs (pools) and exchanges (fluxes) in the atmosphere, biosphere, hydrosphere and lithosphere.

Solar radiation that reaches the top of Earth’s atmosphere has been measured by satellites to be 1,361 W/m². This average annual ‘solar constant’ amounts to a flux of 173,000 TW (173 x 10¹²) of solar radiation for the whole Earth. It includes infrared

(50%), visible (40%) and ultraviolet light (10%). About 30% of solar radiation is reflected back by the atmosphere, clouds and land as shortwave radiation; the remaining 70% is absorbed by land, oceans and atmosphere for various processes, but is eventually radiated back to space. Only 40 TW (0.023%) of solar radiation is involved in photosynthesis, the source of organic matter.

The Carbon Cycle

Photosynthesis and respiration are probably the most familiar processes of the carbon cycle to us. Plants utilise sunlight, carbon dioxide and water to

Carbon budget on Earth.

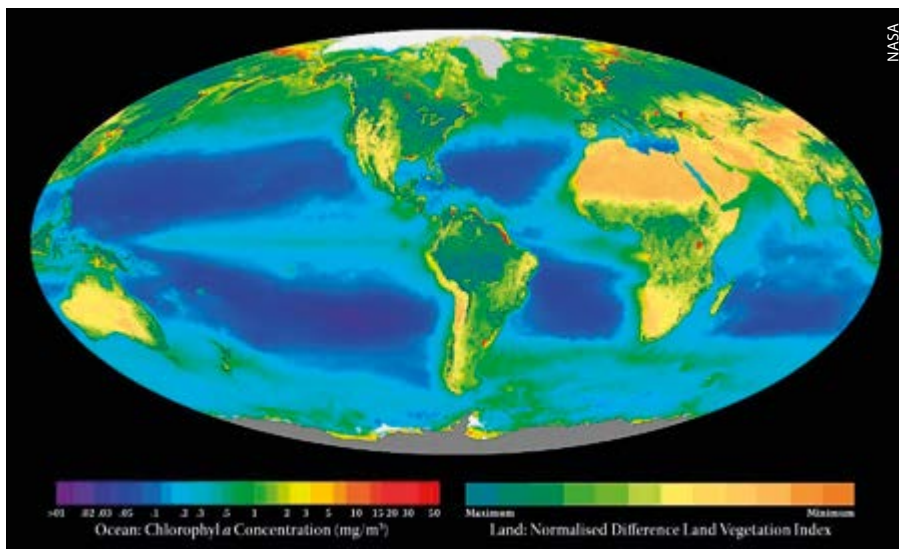
Carbon Pools (Reservoirs)	Quantity (Gigaton, 10 ¹² ton)
Atmosphere	720
Oceans:	38,400
Total inorganic	37,400
Total organic	1,000
Surface layer	670
Deep layer	36,730
Lithosphere:	
Carbonate sediments	>60,000,000
Kerogens	15,000,000
Terrestrial Biosphere (Total):	2,000
Living biomass	600-1,000
Dead biomass	1,200
Aquatic Biosphere:	1-2
Fossil Fuels (Total):	4,130
Coal	3,510
Oil	230
Natural gas	140
Other (peat, etc.)	250

Source: The Global Carbon Cycle, Falkowski et al., Science 13 Oct. 2000

produce food (carbohydrate molecules such as sugars) and oxygen. Animals, in turn, depend on plants (or other animals) for food, and their respiration involves inhalation of oxygen and exhalation of carbon dioxide. Photosynthesis and respiration occur in both terrestrial and aquatic ecosystems, the difference being that land plants and animals utilise the atmospheric carbon dioxide and oxygen while marine organisms (phytoplankton and zooplankton) get these substances from sea water. Note that sunlight also penetrates the upper 200m of oceans – the photic zone, where about 90% of marine organisms live.

Photosynthesis and respiration are parts of the ‘fast carbon cycle’. The ‘slow carbon cycle’, which operates on longer time periods, includes the chemical weathering (thus absorbing atmospheric carbon dioxide) and erosion of rocks, and the transport of organic matter by rivers to oceans, as well as the plate tectonic subduction of carbonate rocks and release of carbon dioxide from volcanoes. The slow carbon cycle carries terrestrial carbon to oceans where it is incorporated in marine organisms or deposited as carbonate rocks on the sea floor.

Since high levels of biological activity increase the production of organic matter, the supply of nutrients – phosphates and nitrates – for organisms is another condition favourable for deposition of rich source rocks. Continental margins with sediment-laden rivers naturally have abundant



Distribution of phytoplankton (primary producers of organic matter in oceans) depicted as concentration of chlorophyll.

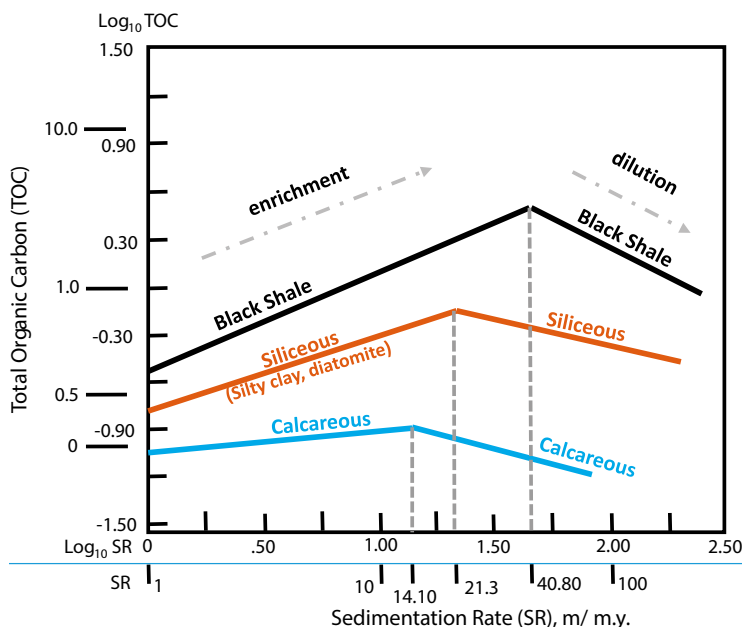
nutrients. Marine ‘upwelling zones’ are also important providers of nutrients to stimulate the growth of phytoplankton populations (primary producers of organic matter). Upwelling is the rise of colder, nutrient-rich water from the ocean bottom to the sea surface, the nutrient content being derived from decomposition of dead plankton. Marine upwelling is caused by various mechanisms. In coastal areas, for example, where winds move parallel to the shore and surface waters move offshore perpendicular to the wind direction, deeper and colder water upwells to the surface. In equatorial coasts, the eastward trade winds drive away surface waters from the western

coastline of the continents, thus inviting deeper colder water to rise and replace the surface waters.

Anoxic Environments and Sedimentation

At present, total production of organic matter in the world’s oceans amounts to 50 billion tons a year, but over 99% of this is broken down by oxidation, microbial activity or physicochemical changes in water column. Therefore, only 0.01–0.001% of organic matter is preserved in sedimentary rocks as kerogen or fossil fuels as part of the ‘slow carbon cycle’. This indicates the preciousness of petroleum resources formed over millions of years, hence their categorisation as non-renewable resources on the human timescale, although petroleum generation is a continuous, renewable process on the geological timescale.

When organic matter combines with oxygen, the reaction produces carbon dioxide and oxygen molecules – the reverse of photosynthesis, and also what happens when we burn fossil fuels. Oxygen thus acts as a double-edged sword: it helps to produce organic matter, yet also destroys it. Therefore, for organic matter to be preserved in sedimentary rocks, an anoxic environment ($O_2 < 0.2$ mL/L) is required. Anoxic conditions are found in lakes with thermally stratified waters (warm water over cold water), in barred near-shore basins with salinity stratification



Relationships between sedimentation rate and total organic carbon for various marine rocks. Data for Jurassic – Recent sediments recovered by the Deep Sea Drilling Project (Johnson Ibach, 1992, AAPG Bulletin, 66: 170-188).

(light water atop dense water), and continental margins at low latitudes (and close to upwelling zones) where water depths of 200–1,500m (below the photic zone) are deficient in oxygen.

Obviously, oceanic anoxic events, during which vast parts of the world's oceans were depleted in oxygen, favour the deposition of organic-rich source rocks. Such events require high levels of atmospheric carbon dioxide (from volcanic eruptions), warm climates (mainly due to atmospheric greenhouse effect), sluggish ocean currents, and euxinic (sulphidic) water chemistry (from volcanic outgassing). Extreme volcanic activity also supplies nutrients that stimulate planktonic productivity in the oceans. Global anoxia have been recorded in the Jurassic and Cretaceous periods – these rocks account for 70% of the world's petroleum reserves. Several intervals of anoxia have also been found throughout the Palaeozoic era. Intense global anoxia have also been linked to marine mass extinctions because of climatic change and toxic (H₂S-rich) waters.

Organic matter in ocean waters exists in three different forms: particulate matter; in solution; and in colloidal form. Particulate organic matter may directly drop to ocean bottom, while dissolved organic matter may be adsorbed onto clay grains, which then sink slowly through the water. Colloidal organic matter flocculates to particulates before sinking.

Organic matter that reaches the

Devonian Marcellus Shale, West Virginia.



sea floor is buried in sediments. It is intuitive to consider that more sedimentation favours the deposition of rich source rocks not only because of the greater volume of sediments, but also because rapid sedimentation and burial impedes oxidation processes, thus preserving organic matter. This is true only to some degree, because high sedimentation rates actually lead to dilution of organic matter in sedimentary rock formations.

A Summing-up

Basins with restricted water circulation and stratified water column will preserve more organic carbon in sediments and produce good source rocks. To sum up our discussion in this article, the following relationship is quoted from a seminal paper by Kevin Bohacs et al. (2005, *SEPM Special Publication 82*, pp. 61-101):

Organic-matter enrichment = Production – (Destruction + Dilution)

Production of organic matter is a function of photosynthesis (sunlight, water, carbon dioxide and nutrient supply) and plankton population. Destruction is related to exposure time to oxidants. Dilution is a function of clastic sedimentation rate and production of biogenic material (silica or carbonate). In short, 'significant enrichment of organic matter occurs where organic-matter production is maximised, destruction is minimised, and dilution by clastic or biogenic material is optimised.' ■



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Back to Source Rocks: Part II

RASOUL SORKHABI, Ph.D

Source rocks constitute the foundation of both conventional and unconventional petroleum systems. The first part of this article (*GEO ExPro*, Vol. 12, No. 6) discussed the formation of organic matter in sediments. Here we review the parameters that make a sedimentary rock an effective petroleum source rock, and the analytical methods used to characterize source rocks for successful petroleum exploration and production.

Although fine-grained, clay-rich rocks with particle sizes less than 1/16 mm account for about 70% of sedimentary rock mass, not all of these are effective source rocks. Petroleum is made up of hydrocarbon molecules originating in a rock in which organic matter (kerogen) is dispersed in the sedimentary formation and has been buried and thus heated enough to transform kerogen to hydrocarbons (i.e. thermal maturity). In addition, the rock formation should have considerable volume (thickness of meters and length of kilometers) in order to generate large amounts of hydrocarbons. Rock volume becomes especially important for exploring shale plays, in which the source, reservoir and seal rock are the same.

Organic Richness

The organic richness of source rocks is measured by total carbon content (TOC), which is described in weight percentage of the sample. Rocks are ranked from poor to excellent; higher percentages of TOC indicate organic-rich sedimentary rock.

Direct methods of measuring TOC are made by the Leco carbon analyzer. About a gram of powdered sample is treated with acid to remove the inorganic carbon (carbonate). The dried residue is then mixed with a metal accelerator (iron and copper), and combusted (rapid reaction with oxygen) using a high-frequency induction furnace (1,200–1,400°C). The mass of the carbon dioxide gas thus formed is

	TOC in shale	TOC in Carbonate
Poor	<0.5%	<0.2%
Fair	0.5–1.0%	0.2–0.5%
Good	1–2%	0.5–1%
Very Good	2–5%	1–2%
Excellent	>5%	>2%

Source rock ranking based on TOC.

measured in a non-dispersive infrared detection cell and converted to percent carbon based on the dry sample weight. TOC values can be underestimated if there is loss of immature organic carbon in the acid treatment or overestimated if carbonate is not completely removed prior to analysis.

Indirect methods of estimating

Jurassic Oxford Clay outcropping near Weymouth, England.



TOC include pyrolysis (see below) and well logs. A high content of organic matter in sedimentary rocks gives positive (high) feedback in gamma-ray and neutron logs, and results in high transit time in sonic log, high resistivity and low density (if free hydrocarbon molecules occupy pores). Recently, some geophysicists have also attempted to locate very high TOC sedimentary layers by their significantly low acoustic impedance on seismic data (Løseth et al., 2011).

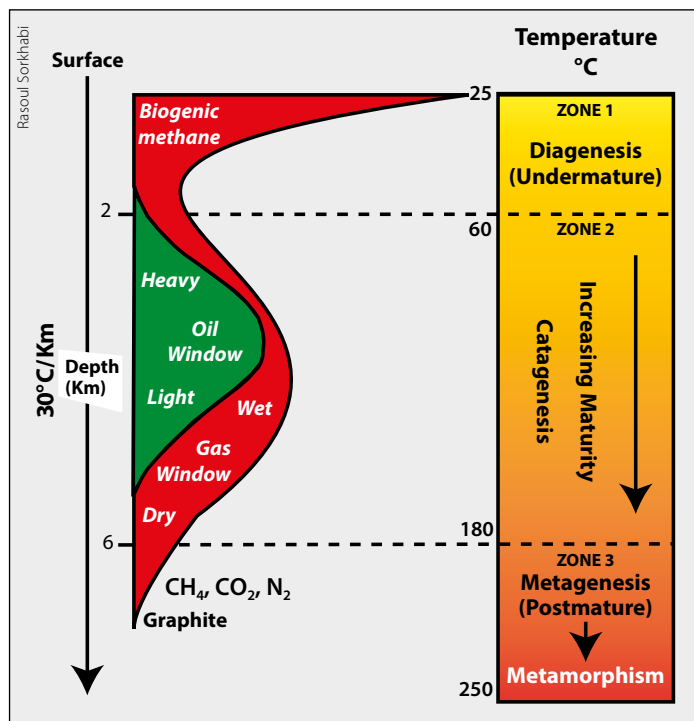
In interpreting TOC values for prospect evaluation, one needs to consider sample lithology, sampling procedure and the TOC measurement method. For surface sampling, the specimen should not come from the exposed surface, although even then, outcrop samples will often yield lower TOCs compared to samples of the same formation collected from cores because of weathering of surface rocks. Several regularly spaced samples from the entire thickness of a formation should be collected – a single sample from an organic-rich or organic-poor layer of the formation could be misleading.

TOC data based on a large number of sample analyses from around the world provide some guidelines for prospect evaluation, suggesting average TOC of all shales is 0.9%; for shale source rock it averages 2.2%; for calcareous shales 1.9%; for carbonate sources 0.7%; and the average for all source rocks is 2.2% (Tissot and Welte, 1984). In general, dark, laminated clay-rich sedimentary rocks with no bioturbation are indicative of organic carbon content and anoxic depositional environments, thus often making good source rocks.

Thermal Maturity Indicators

Burial temperature ‘cracks’ the complex kerogen molecules into simpler hydrocarbons. There are several methods of estimating the thermal maturity of a source rock. Burial history (stratigraphic time vs. burial depth curve) together with reasonable

Petroleum geologists usually divide the burial depth-temperature zones in a sedimentary basin into three zones from top to bottom (with increasing temperature). (1) The zone of diagenesis, compaction and cementation converts loose sediment into sedimentary rock. In this shallow zone, bacterial action on organic matter produces biogenic (microbial) methane gas. (2) The zone of catagenesis corresponds to oil and gas windows. (3) In the zone of metagenesis, thermogenic methane as well as non-hydrocarbon gases (carbon dioxide, nitrogen, and hydrogen sulfide) evolve. At deeper levels, the rock enters the zone of metamorphism (involving mineralogical and textural changes). The entire transformation sequence consists of (1) kerogen (insoluble in organic solvents); (2) bitumen (solid hydrocarbon soluble in organic solvents); (3) heavy oil; (4) light oil; (5) condensate/wet gas; (6) thermogenic dry gas (methane) and non-hydrocarbon gases; and (7) residue carbon or graphite. Catagenesis is governed by chemical kinetics of kerogen; for every 10°C increase, the cracking of kerogen doubles (Waples, 1980).



assumption of geothermal gradients informs us whether the target layer ever resided in the oil or gas window zone.

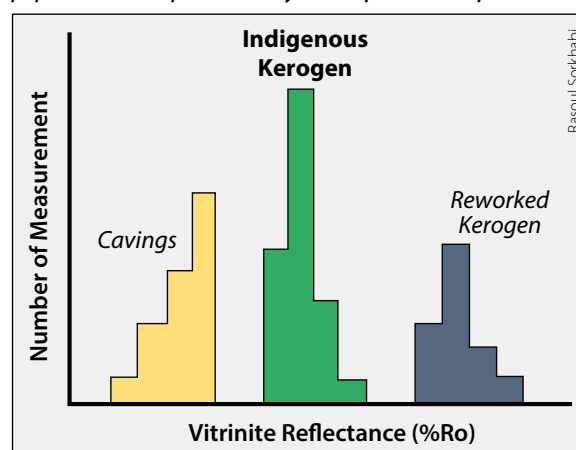
A common method for estimating sample paleotemperature (maturity) is vitrinite reflectance (VR or Ro). Vitrinite is a type of maceral particle derived from the cell-wall or woody tissue of plants, and is found in coal and kerogen. It has a shiny (vitreous, from the Latin *virtum*, glass) appearance which irreversibly increases with increasing temperatures (due to aromatization).

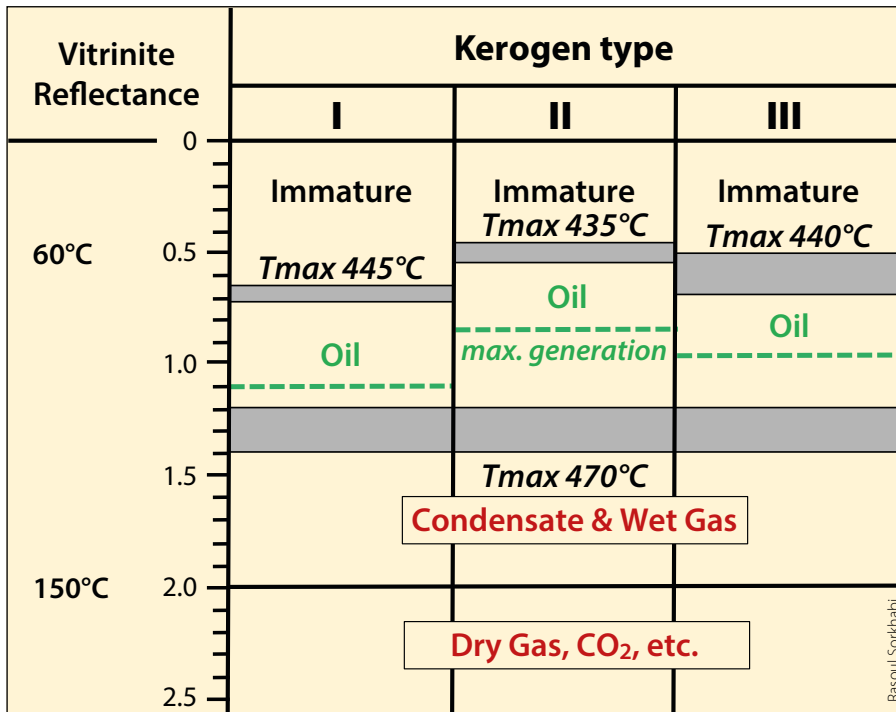
VR analysis may be performed on whole rock powder or on kerogen extracts from the rock. The sample is mounted on epoxy resin or similar material and is observed under a reflected light microscope. The reflectance (%Ro = % reflectance in oil-immersion objective lens) of vitrinite particles can be used to evaluate the thermal maturity of rocks. The VR scale has been calibrated empirically and experimentally, and is

widely used in the petroleum industry.

At least 50 vitrinite particles should ideally be measured for each sample. The data are plotted in the form of a histogram that gives the minimum, maximum and mean values of Ro as well as the number of data points and standard deviation. Sometimes the histogram gives a complicated distribution with more than one cluster, in which case results should be interpreted considering sample conditions as well as data distribution. Lower Ro values probably indicate contamination of the sample by caving,

Histogram of vitrinite reflectance data with more than one population and a plausible way to interpret the sample.





Effects on kerogen type on the onset of oil window (modified after Tissot and Welte, 1984).

(i.e. immature kerogen from shallower levels caving into the borehole). Alternatively, higher values may come from reworked kerogen eroded from a more mature rock.

The onset of oil generation corresponds to Ro values of 0.5–0.6% and the maximum generation of oil to 0.85–1.1%. The onset of gas generation (wet gas and condensate) generally corresponds to Ro values of 1.0–1.3% and the gas window continues for Ro values of 3% for dry gas. Temperatures and corresponding Ro values will vary for different types of kerogen present in the source rock.

VR cannot directly be used for samples older than Devonian because land plants only flourished on Earth after then. For Early Paleozoic rocks, graptolite reflectance or conodont alteration index (CAI) can be used. VR scale has also been calibrated for reflectance of bitumen (solid hydrocarbon), so samples lacking vitrinite particles can be measured for bitumen reflectance, and 'VR equivalent' values are then obtained. VR

equivalent values can also be calculated from pyrolysis (see below).

Another important technique for estimating thermal maturity is the Thermal Alteration Index (TAI) based on color changes (from light yellow through orange and brown to black) in spores and pollen as a result of the burial heat the sample has experienced. Several TAI scales relating the observed color under the microscope to temperature have been formulated by scientists. The oil window corresponds to TAI values of 2.6–3.3.

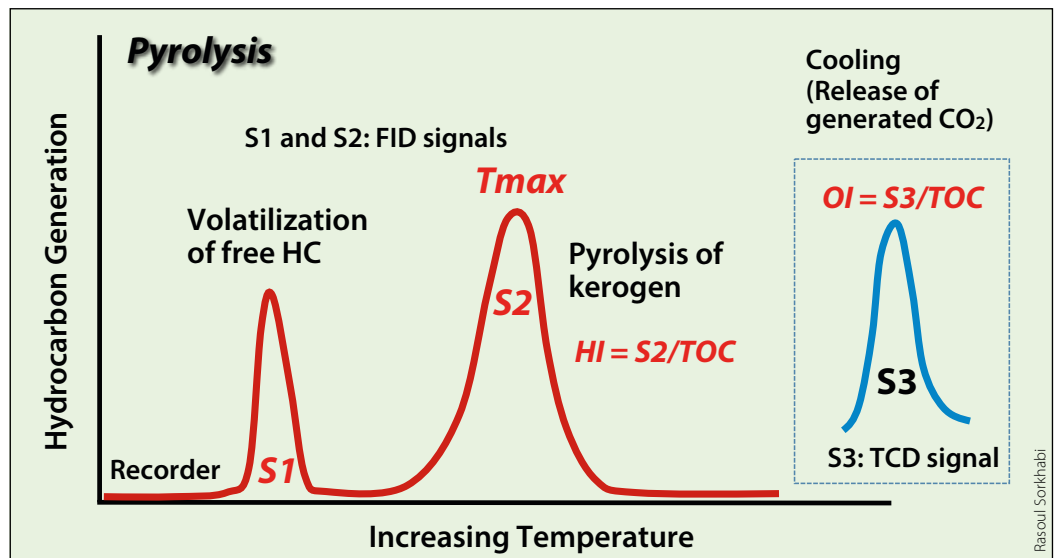
For samples which have been analyzed by pyrolysis the results include a parameter called Tmax, which is also a paleo-temperature indicator. The oil window corresponds to Tmax values of 435–470°C.

Petrographic methods such as VR provide information about the maximum temperature that the rock experienced in the past but they do not tell us about timing. A comparison of VR or similar data with the burial curve is one way to assess the rock's thermal history. Another is fission-track thermochronology of apatite minerals separated from sandstone layers adjacent to the source rock. Uranium fission tracks in apatite shorten at temperatures of 60–120°C, which correspond to the oil window temperatures. Therefore, by determining the fission-track age and the track lengths in apatite, one can reconstruct the time-temperature pathway of the rock sample (GEO ExPro, Vol. 7, No. 1).

Pyrolysis

Pyrolysis is the process of heating a rock or kerogen sample in the laboratory in order to measure the type, richness and maturity of hydrocarbons by thermal decomposition in the absence of oxygen. This can be done either in the presence of water (hydrous) or in its absence (anhydrous). RockEval™, developed by the Institut Français du Pétrole, is a programmed instrument for anhydrous pyrolysis of rock samples. Similar instruments include the Source Rock

Various terms related to pyrolysis of a source rock sample in the laboratory.



Analyzer™ by Weatherford Laboratories Instruments and HAWK by Wildcat Technologies.

In pyrolysis, nearly 100 mg of crushed, dried rock sample is progressively heated (~25°C/minute) up to at least 550°C under an inert helium or nitrogen atmosphere. The first step is to heat it to 300°C to volatilize the pre-existing free hydrocarbons in the sample. The amount of these hydrocarbons is measured from a peak area (S1). The next step is to pyrolyze the kerogen present in the sample at higher temperatures and measure it at peak area S2. The carbon dioxide generated from the cracking of kerogen (up to 390°C) is collected as S3. S1 and S2 are measured by the Flame Ionization Detector (FID), and S3 by the Thermal Conductivity Detector (TCD). Residual carbon in the sample is also collected and measured as S4 (at 600°C). All of these peak areas are expressed in units of mg/g rock. High S1 indicates an active source rock while S2 values measure the remaining hydrocarbon-generating potential of the rock. Tmax is measured from the S2 peak.



Outcrop of Ordovician oil shale (kukersite) in Estonia.

Data from pyrolysis are used to calculate the following parameters:

Hydrogen Index (HI) = (S2 x 100) mg/g / %TOC; HI values of >600 indicate oil-prone kerogen type I while those of <200 indicate gas-prone kerogen type III.

Oxygen Index (OI) = (S3 x 100) mg/g / %TOC; OI values of >50 are indicative of immature kerogen.

Production (Generation) Index (PI or GI) or **Transformation Ratio (TR)** = S1 / (S1/S2); PI values of 0.1–0.4 correspond

disruptive;

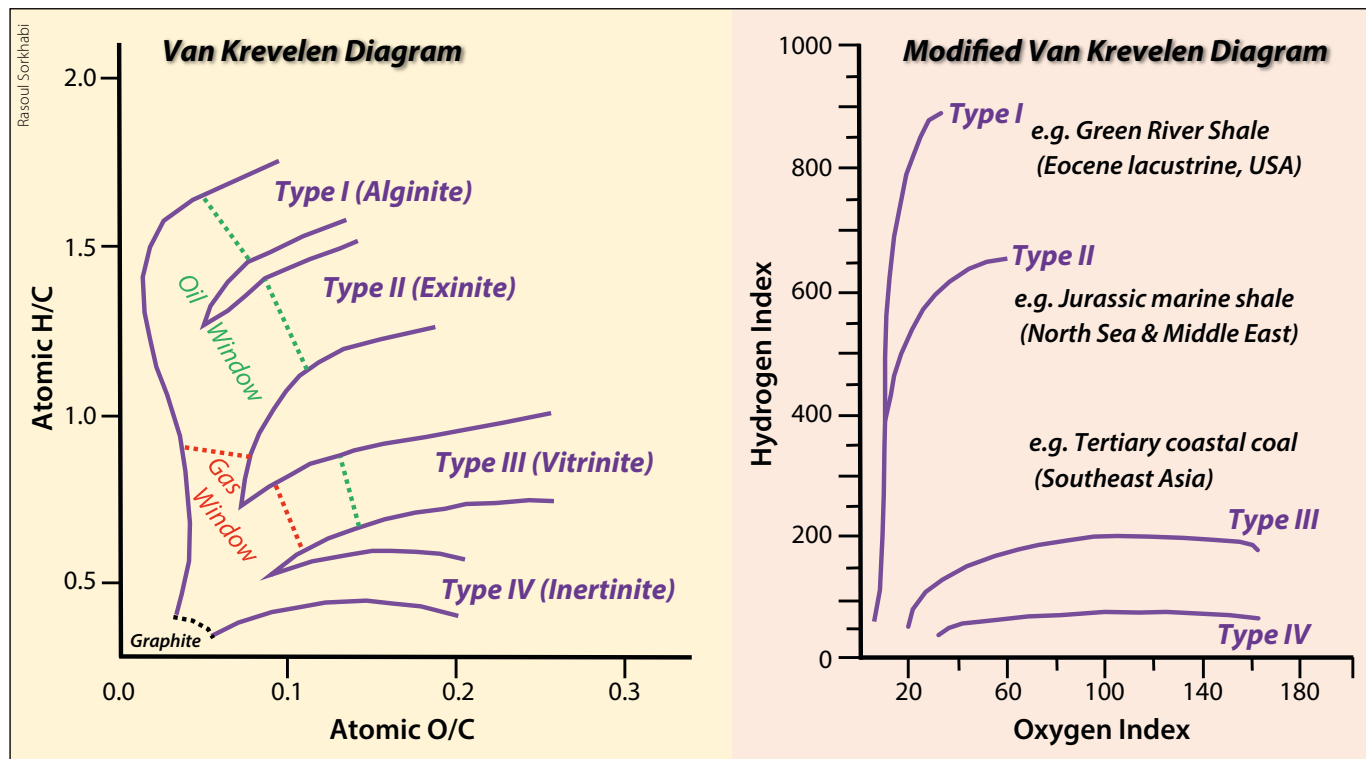
adj. relating to or noting a new product, service, or idea that radically changes an industry or business strategy, especially by creating a new market and disrupting an existing one.

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Kerogen types plotted on the Van Krevelen and Modified Van Krevelen diagrams. (Rasoul Sorkhabi from Tissot and Welte, 1984, and other sources.)

to the oil window. Lower values are for immature source rock and higher values indicate gas generation to destruction.

Potential Yield (PY) or Generative Potential (GP) = S1 + S2 (mg/g or kg/ton of rock): PY values of <2 indicate poor yield, those between 2–4 fair and >6 very good.

Calculated Vitrinite Reflectance = $0.018 \times T_{max} - 7.16$ (Jarvie, 2012).

Calculated TOC = $[0.082 (S1 + S2) + S4] / 10$ (Espitalié, Deroo and Marquis et al., 1985): Calculated TOC is the sum of carbon obtained in pyrolysis of the sample.

Kerogen Types

Kerogen is categorized into four types:

Type I is derived from lipid-rich algal material (alginite) preserved in anaerobic environments, especially lacustrine and similar marine conditions. This kerogen is abundant in aliphatic (non-aromatic) compounds, and is highly oil prone.

Type II, rich in liptinic macerals, is derived from waxy and resinous parts of plants including extinite (skins of spores, pollen, and cuticles of leaves and herbaceous plants) and

degraded, amorphous phytoplankton from marine environments. This type commonly has higher amounts of sulfur than other kerogens. It is mainly alicyclic (naphthenic) and produces moderate amounts of both oil and gas.

Type III is relatively hydrogen-poor, predominantly vitrinite macerals, derived from terrestrial woody and fibrous plant fragments and structureless, colloidal humic matter. It is rich in aromatic compounds, and mainly gas prone, although liptinitic kerogen, if present >15% in the sediments, also generates oil. Kerogen type III is deposited in terrestrial or shallow marine environments. Coals usually contain this type of kerogen.

Type IV refers to extremely hydrogen-poor, carbon-rich residual (reworked from older sediments) or oxidized kerogen. It is the chemical equivalent of inertinite maceral group, and is considered as dead carbon with no potential for generating oil and gas.

The Dutch chemist Dirk Willem van Krevelen (1914–2001) noted that various kerogens can be recognized on the basis of their atomic H/C versus O/C plots. In the 1970s French

petroleum chemists Bernard Tissot and J. Espitalié extended van Krevelen’s work from coal to kerogen and substituted the elemental parameters with Hydrogen Index and Oxygen Index obtained from pyrolysis (a pseudo- or modified Van Krevelen diagram). In this analysis, kerogen type I has H/C >1.5 and HI >600; type II has H/C of 1.0 to 1.5 and HI of 200 to 600; type III has H/C of 0.7 to 1 and HI of 50 to 200; and kerogen type IV has H/C of <0.7 and HI of <50 (Peters and Cassa, 1994).

Geochemical Logs and Basin Modeling

Geochemical data from single or multiple source rock horizons can be plotted as geochemical logs for wells in order to compare and contrast the data vertically and horizontally. If there are considerable data from various wells, specific parameters, such as TOC or VR, may also be plotted on formation top maps and contoured to decipher lateral variations. Basin modeling indeed began with source rock burial-maturity-generation modeling in the early 1980s, and source rock data still constitute the critical input data for basin modeling software packages.

References available online ■