

UNICORNS IN THE GARDEN OF GOOD AND EVIL: Part 8 – Igneous and Metamorphic Reservoirs

By E. R. (Ross) Crain, P.Eng.

Unicorns are beautiful, mythical beasts, much sought after by us mere mortals. The same is true for petrophysical models for unconventional reservoirs. This is the eighth in a series of review articles outlining the simple beauty of some practical methods for log analysis of the unusual.

IGNEOUS AND METAMORPHIC BASICS

Igneous and metamorphic rocks form reservoirs in many parts of the world. Reservoir quality varies and most benefit from natural fractures. Although some geologists believe the hydrocarbons in some granite reservoirs comes from deep in the earth, the majority of these reservoirs can be shown to contain hydrocarbons that migrated from conventional sedimentary sources.

As a generalization, metamorphic rocks are rocks that have been exposed to high heat and pressure. The main causes are:

- Contact metamorphism – changes in the rock due to heat from a nearby magma source.
- Regional metamorphism – changes caused by widespread elevated heat and pressure.
- Hydrothermal metamorphism – chemical changes in the rock due to the circulation of hot liquids through the rock fractures.
- Fault-zone metamorphism – metamorphic changes caused by friction at fault movements.

My personal experience is that density, neutron, sonic, and photoelectric values for metamorphic rocks are the same as the sedimentary equivalent, although this may not be universally true.

The change in the rock is based on the amount of heat and pressure applied to it, as well as the fluids available during the metamorphic processes. Changes that occur during metamorphism include:

- Small crystals re-form to create larger crystals of the same minerals (re-crystallization).
- New minerals are created from the original mineral composition (neomorphism).
- New minerals are created by gaining or losing elemental components.

Specific sedimentary rocks become specific metamorphic rocks, as shown in Table 1.



Figure 1. Eyjafjallajökull volcano, Iceland, 2010.

Igneous rocks are classified in several ways – by composition, texture, and method of emplacement. Generally speaking, the composition (mineral mixture) determines the log response, the texture determines the name used for the mineral mixture, and the method of emplacement determines the texture and internal porosity structure (if any).

Intrusive igneous rocks are formed inside the earth. This type of igneous rock cools very slowly and is produced by magma from the interior of the earth. They have large grains, may contain gas pockets, and frequently have a high fraction of silicate minerals. Intrusions are called sills when oriented

Parent Rock	Metamorphic Equivalent
Sandstone	Quartzite
Limestone, Dolomite	Marble
Basalt	Schist or Amphibolite
Shale	Slate
Granite	Schist
Rhyolite	Schist

Table 1. Metamorphic rock origins.

roughly horizontal and dikes when near vertical. Extrusive igneous rocks form on the surface of the earth from lava flows. These

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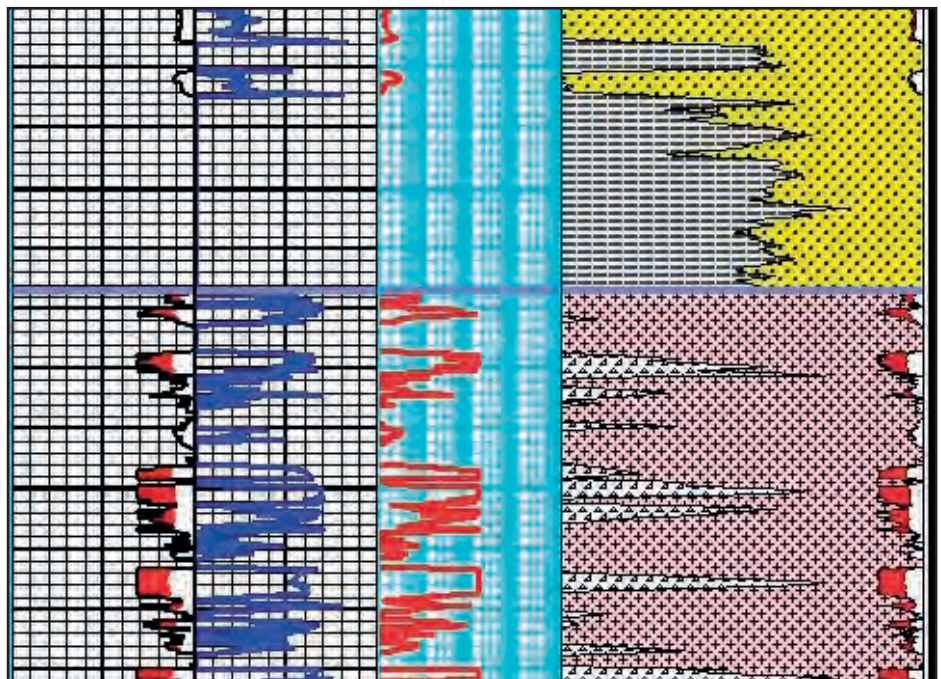


Figure 2. Granite Wash (yellow) and shale (gray) above granite (white) and diorite (tan). Porosity and lithology are calculated from conventional density, neutron, and PE methods. Both zones are radioactive, so the GR is not used for shale volume.

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cool quickly, resulting in small grain sizes. They typically contain little to no gas from the initial formation.

Both intrusive and extrusive rocks may contain natural fractures created by contraction while cooling, and may have carried other rock fragments with them, called xenoliths. Intrusive rocks may alter the rocks above and below them by metamorphosing (baking) the rock near the intrusion. Extrusives only heat the rock below them, and may not cause much alteration due to rapid cooling. Extrusives can be buried by later sedimentation, and are difficult to distinguish from intrusives, except by their chemical composition and grain size.

The mineral composition of an igneous rock depends on where and how the rock was formed. Magmas around the world have different mineralogical compositions.

- Felsic igneous rocks are light in color and are mostly made up of feldspars and silicates. Common minerals found in felsic rock include quartz, plagioclase feldspar, potassium feldspar (orthoclase), and muscovite. They may contain up to 15% mafic mineral crystals and have a low density.
- Mafic igneous rocks are dark colored and consist mainly of magnesium and iron. Common minerals found in mafic rocks include olivine, pyroxene, amphibole, and biotite. They contain about 46-85% mafic mineral crystals and have a high density.
- Ultramafic igneous rocks are very dark colored and contain higher amounts of the same common minerals as mafic rocks, but with about 86-100% mafic mineral crystals.
- Intermediate igneous rocks are between light and dark colored. They share minerals with both felsic and mafic rocks. They contain 15 to 45% mafic minerals.
- Plutonic and volcanic rocks generally have very low porosity and permeability. Natural fractures may enhance porosity by allowing solution of feldspar grains. Some examples with average porosity as high as 17% are known.

Tuffs and tuffaceous rocks have high total porosity because of vugs or vesicles in a glassy matrix. This is most common in pyroclastic deposits. Interparticle porosity may also exist. Some effort has to be made to separate ineffective microporosity from the total porosity. Pumice (a form of tuff) has enough ineffective porosity to allow the rock to float!

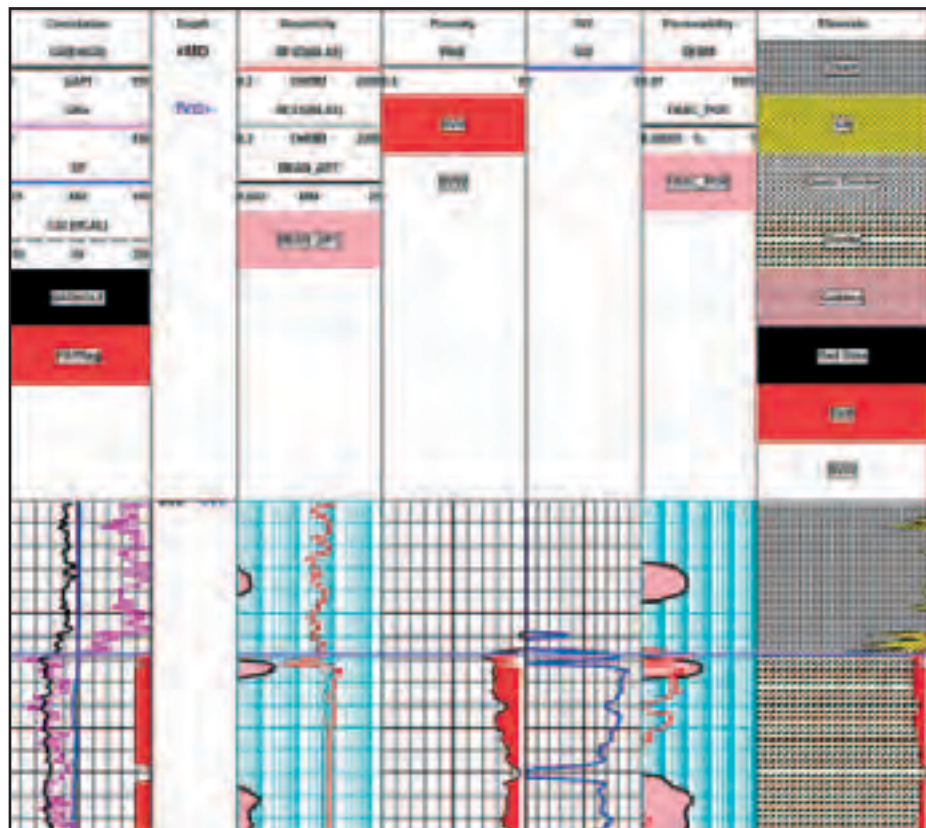


Figure 3. Diorite intrusion covered by shale, open fracture visible as low resistivity spike at top of diorite. Fracture aperture (Track 2) and fracture porosity (Track 5) are from resistivity image processing.

The numerical data in Table 3 has worked well in igneous reservoirs using standard lithology models given earlier in this chapter (Mlich-Nlith, DENSma-Uma, etc). The table is in imperial units. If you work in metric

units: divide neutron values by 100; multiply density by 1,000; and multiply sonic by 3.281. All these values have a moderate range (+/- 10%) and some tuning may be necessary. Don't forget to convert to metric as needed.

Plutonic - Coarse Crystalline	Volcanic - Fine Crystalline	Pyroclastic - Glassy	Silica Content	Gamma Ray - Density
Quartzite			Highest	Lowest
Granite	Rhyolite	Rhyolite Tuff		
Granodiorite	Dacite	Dacite Tuff		
Quartzdiorite	Andesite	Andesite Tuff		
Diorite	Basalt	Zeolite Tuff		
Gabbro	Dolerite			
Diabase				
Dunite			Lowest	Highest

Table 2. Igneous rock classification.

Rock Type	DENSMA	PE	UMA	PHINMA	DTC_MA	DTS_MA
Quartzite	2.65	1.82	4.82	0	55	101.2
Granite	2.65	2.7	7	1	50.8	82.7
Granodiorite	2.72	3.25	8.75	2	55	97.1
Quartzdiorite	2.81	3.56	9.91	3.5	57	89.9
Diorite	2.85	3.95	11	4	57.1	96.8
Gabbro	2.94	4.8	13.3	5	42.4	90.1
Diabase	2.98				44.6	85.8
Dunite	3.29	3.4	11.2	4	38.2	76.9

Table 3. Matrix properties for igneous rocks.

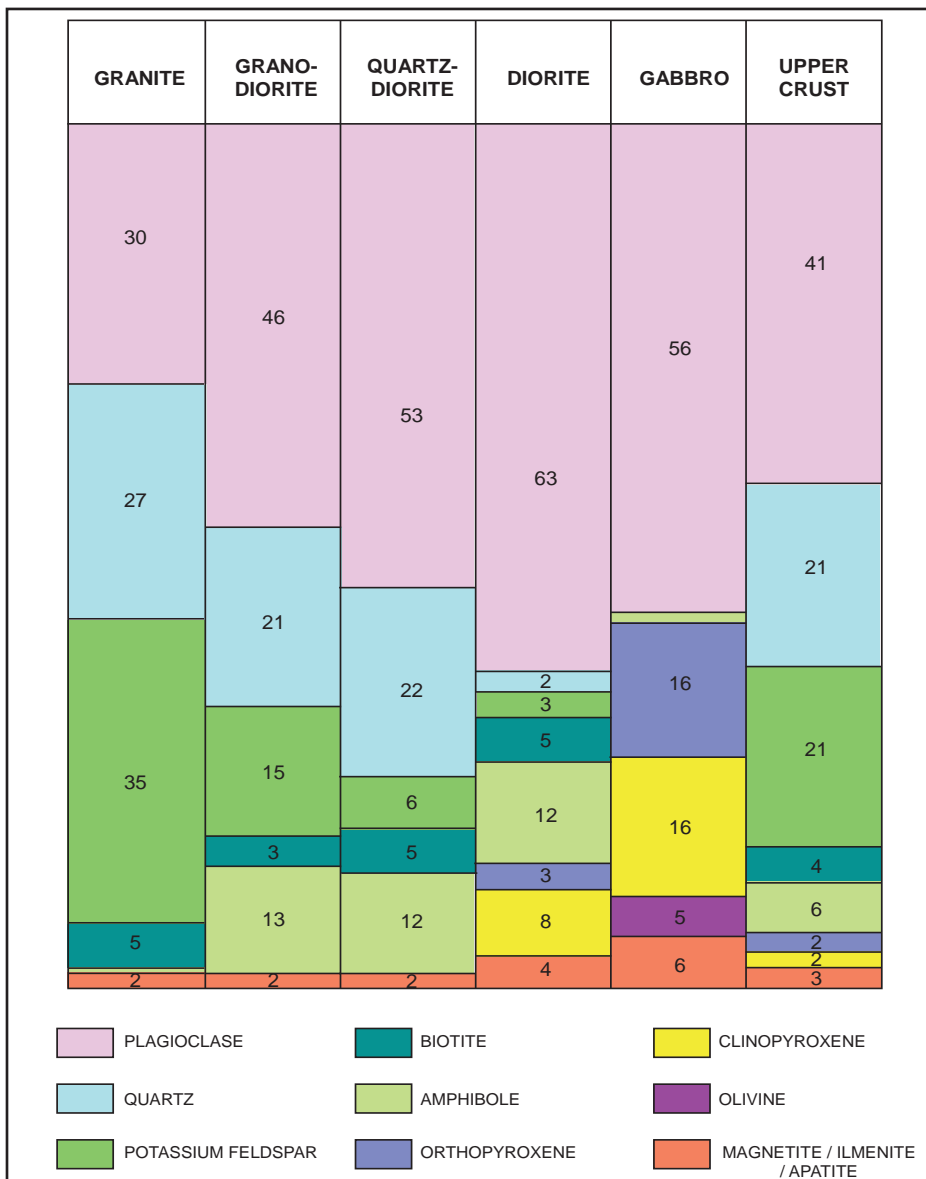


Figure 4. Typical igneous rock mineral composition (courtesy Schlumberger).

Use these matrix values in matrix density or PE crossplots.

Since a typical log suite can solve for three or four minerals at best, you need to choose the dominant minerals and zone your work carefully. If you have additional useful log curves, you might try for more minerals or set up several four-mineral models in a probabilistic solution. A good core or sample description will help you choose a reasonable mineral suite.

Sometimes lithology is determined by triggers. For example, where basalt beds are interspersed between conventional granites or quartzites, it is easy to use the PE or density logs to trigger basalt, leaving the remaining minerals to be defined by a two- or three-mineral model. This approach is widely used in sedimentary sequences to trigger anhydrite, coal, or salt.

Two crossplots are useful for rock identification in metamorphic rocks, as shown in Figures 5 and 6.

METAMORPHIC SAND / GRANITE RESERVOIR EXAMPLE

Figure 7 is a granite / metamorphic rock example from Indonesia. The reservoir has a porosity-enhanced (possibly by fracture-related solution) granite at the base, metamorphosed sandstone and shale above, topped by unmetamorphosed sandstone and shale. Porosity is moderately low throughout, but the gas column is continuous. Interbedded shales (schist or gneiss in the metamorphic interval) are present but do not act as barriers to vertical flow.

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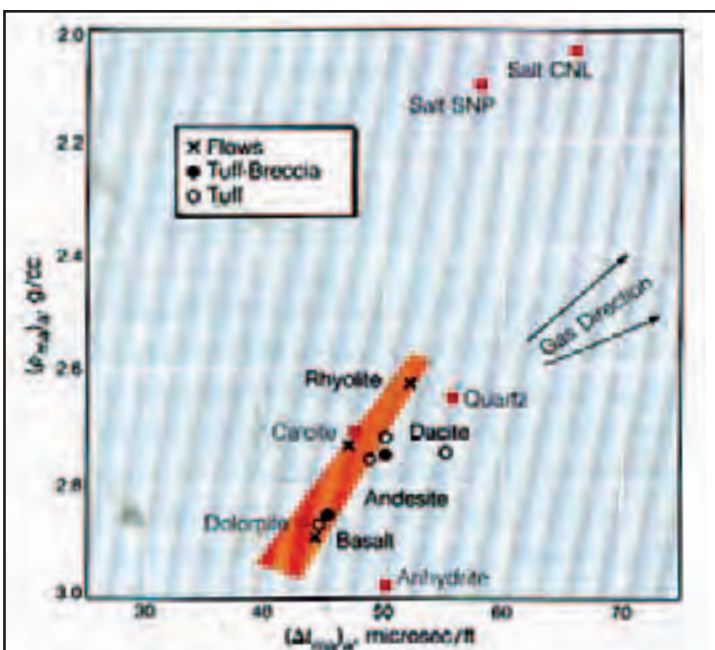


Figure 5. DENSMA vs. DELTMA Plot (courtesy Schlumberger).

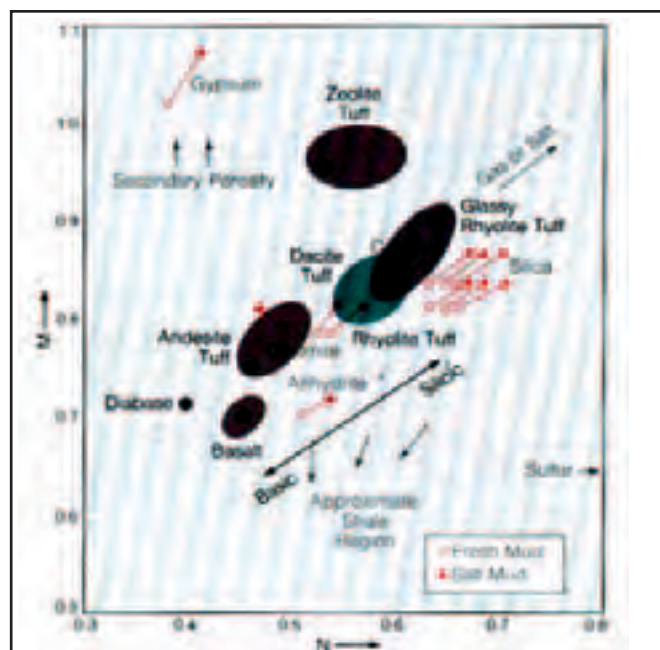


Figure 6. Mlith vs. Nlith Plot (courtesy Schlumberger).

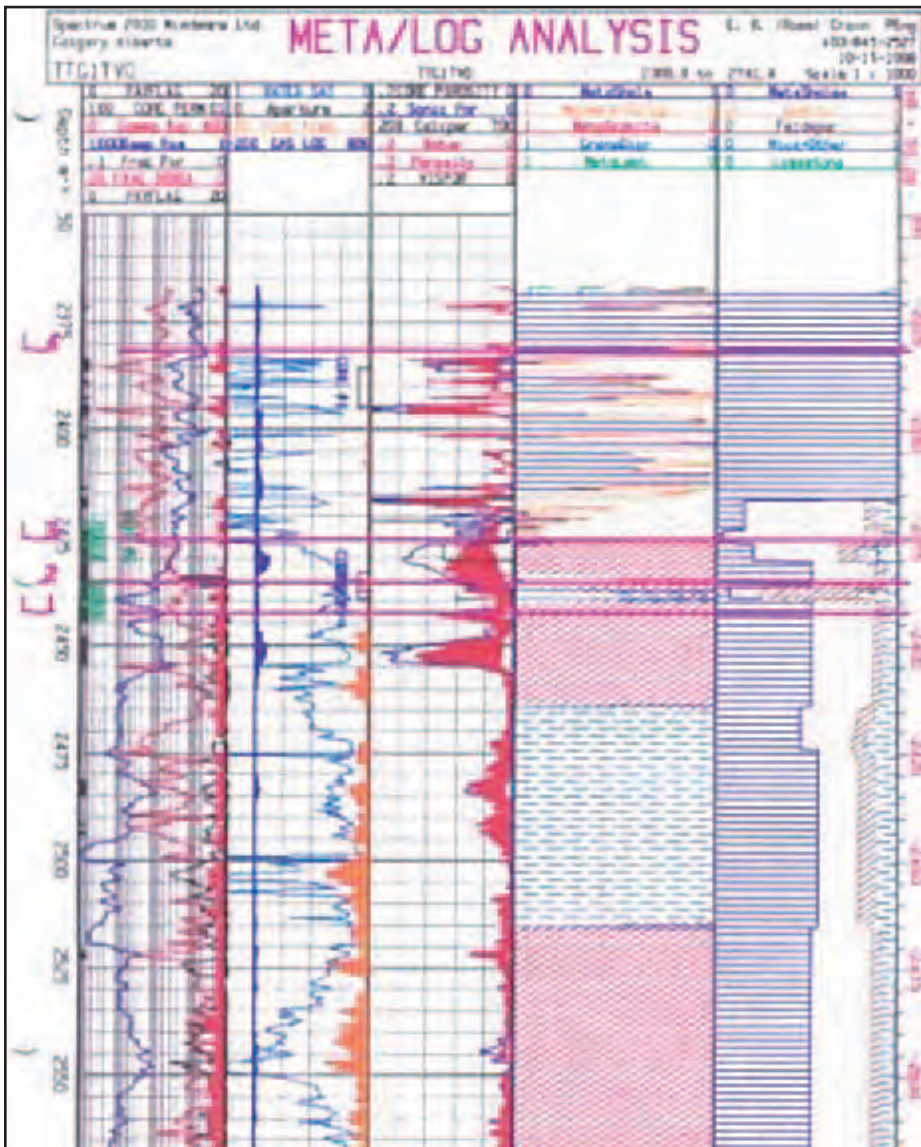


Figure 7. Metamorphic / Granite example with quantitative sample description, calculated lithology, log analysis porosity, saturation, and permeability, with core porosity and permeability overlay. A production log cumulative productivity curve was overlaid on a similar curve generated from log analysis flow capacity (KH). Since this is a gas play, cutoffs are quite liberal.

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In this case, the mineralogy was triggered by quantitative sample descriptions, which in turn were keyed to raw log response to minimize cavings and depth control issues. Porosity and water saturation were derived from conventional log analysis methods. The reservoir is naturally fractured and a fracture-intensity curve was generated from anomalies on the open-hole logs. This was compared to the fracture intensity from resistivity micro-image log data.

Quantitative sample description of mineral composition is shown in track five (right-hand track). Interpreted lithology is in track four; computed porosity in track three (middle track). The log analysis porosity matches core reasonably well (center track) and open-hole fracture indicators (right edge of track one) correspond to resistivity image log data (left edge of track two).

FRACTURED GRANITE RESERVOIR EXAMPLE

Most people forget that there are many unconventional reservoirs in the world,

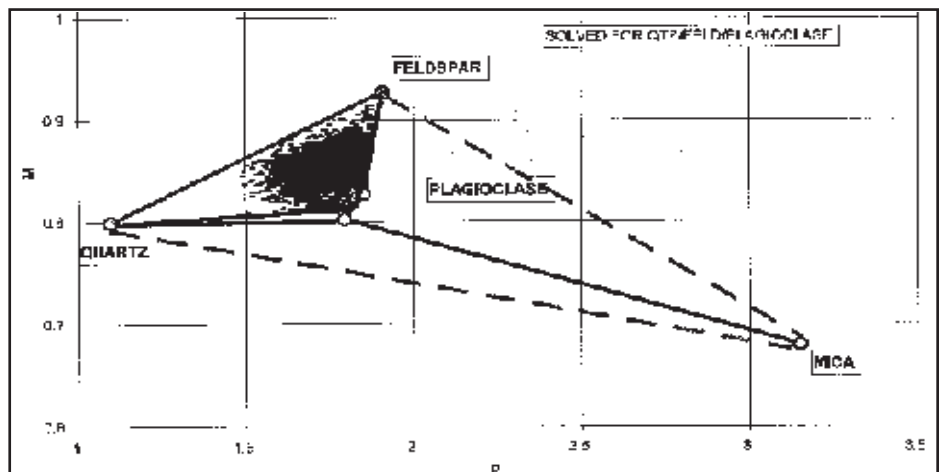


Figure 9. Mlith vs. Plith crossplot for granite (micaceous data excluded).

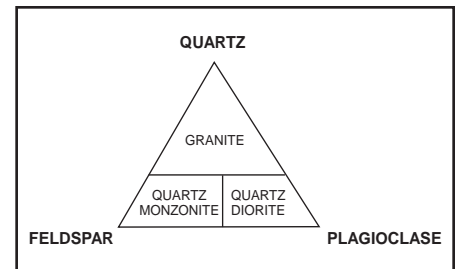


Figure 8. Ternary Diagram for Granite.

which include igneous (extrusive and intrusive) and metamorphic rocks. Granite reservoirs are prolific in Viet Nam, Libya, and Indonesia. Lesser-known granite reservoirs exist in Venezuela, United States, Russia, and elsewhere. Indonesia is blessed with a combination sedimentary, metamorphic, and granite reservoir with a single gas leg. Japan boasts a variety of volcanic reservoirs.

Log analysis in these reservoirs requires good geological input as to mineralogy, oil or gas shows, and porosity. Good coring and sample-description programs are essential, as are production tests. The analyst often has to separate ineffective (disconnected vugs) from effective porosity and account for fracture porosity and permeability. All the usual mineral identification crossplots are useful, but the mineral mix may be very different than that in normal reservoirs. Many such reservoirs seem to have no water zone and most have unusual electrical properties (A, M, N), so capillary pressure data is usually needed to calibrate water saturation.

In an example from the Bach Ho (White Tiger) Field in Viet Nam (see Figures 9, 10, and 11), the mineral assemblage was defined by the ternary diagram in Figure 8. The three minerals (quartz, feldspar, and plagioclase) were computed from a modified Mlith vs. Nlith model, in which PE was substituted for PHIN in the Nlith equation. If data fell too far outside the triangle, mica was exchanged for the quartz.

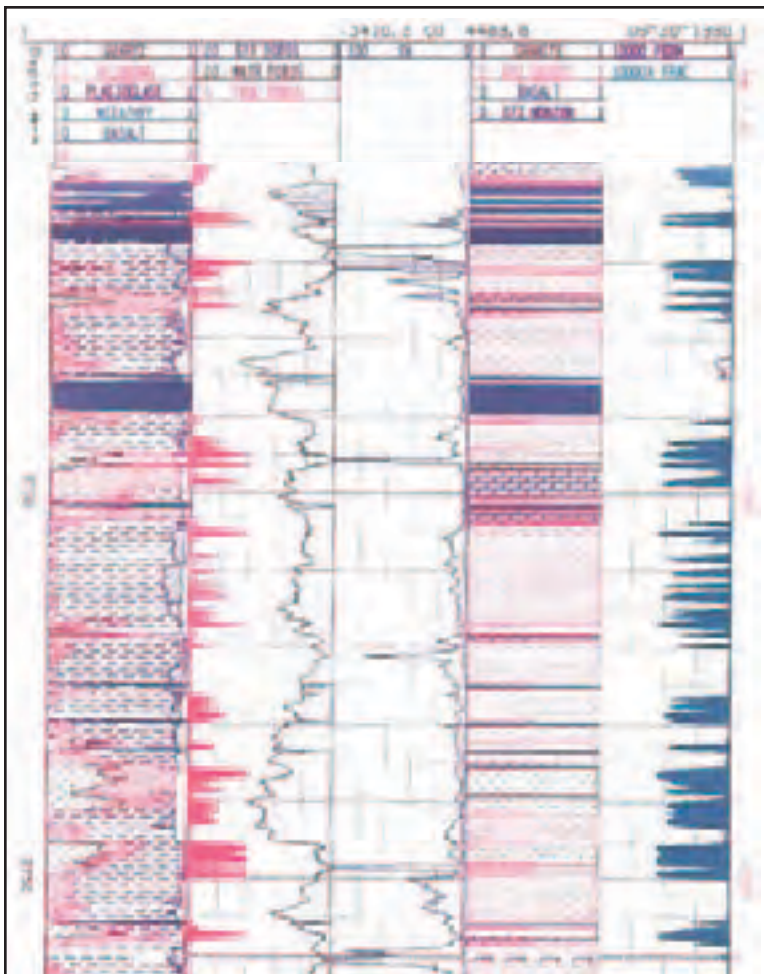


Figure 10. Depth plot for a granite reservoir.

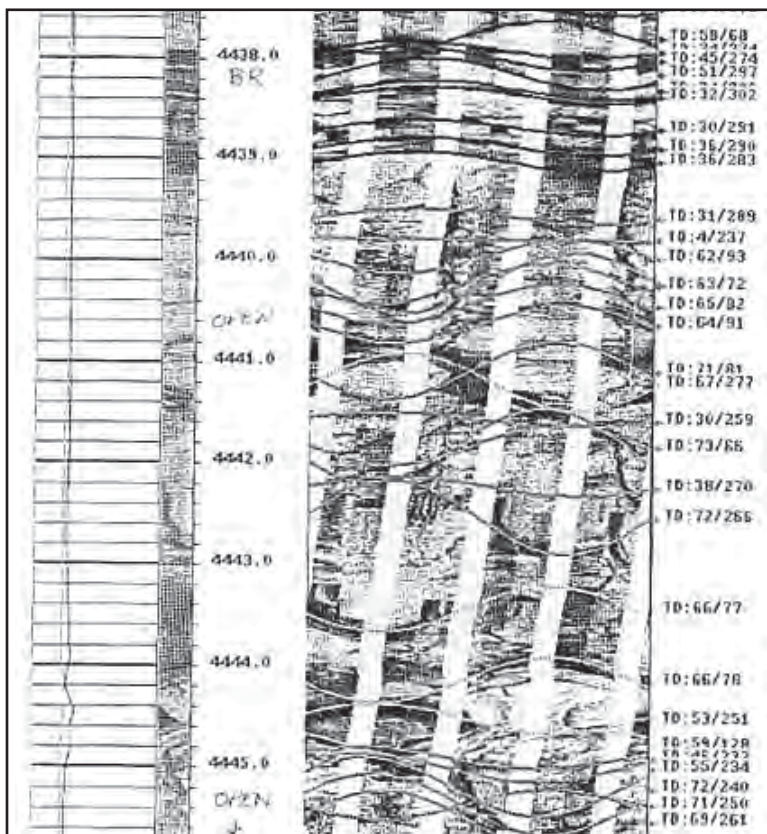


Figure 11. Resistivity micro-scanner image in a granite reservoir – dominant dips are 60 to 75 degrees from horizontal.

Three rock types – granite, diorite, and monzonite – were derived from the three minerals. A trigger was set to detect basalt intrusions. A sample crossplot in Figure 9 shows how the lithology model effectively separates the minerals.

A sample of the log analysis plot is shown in Figure 10. The average porosity from core and logs is only 0.018 (1.8%) and matrix permeability is only 0.05 mD. However, solution porosity related to fractures can reach 17% and permeability can easily reach higher than several Darcies. Customized formulae were devised to estimate these properties from logs, based on core and test data. My colleague, Bill Clow, devised most of the methods used on this project.

Note the fracture porosity and permeability derived from open-hole log data. Fracture porosity from resistivity micro-scanner logs was also computed where available to help control the open-hole work. A black and white resistivity image log, Figure 11, shows some of the fractures. Both high- and low-angle fractures co-exist.

It is clear that non-conventional reservoirs may need some extra effort, customized models, and unique presentations. Everything you need to develop these techniques can be found elsewhere in my handbook (Crain's Petrophysical Handbook on CD-ROM). The mineral properties need to be chosen carefully, but the mathematical models don't change too much.



ABOUT THE AUTHOR

E. R. (Ross) Crain, P.Eng., is a consulting petrophysicist and a Professional Engineer with over 45 years of experience in reservoir description, petrophysical analysis, and management. He has been a specialist in the integration of well log analysis and petrophysics with geophysical, geological, engineering, and simulation phases of oil and gas exploration and exploitation, with widespread Canadian and Overseas experience.

His textbook, "Crain's Petrophysical Handbook on CD-ROM" is widely used as a reference to practical log analysis. Mr. Crain is a Honorary Member and Past President of the Canadian Well Logging Society (CWLS), a Member of Society of Petrophysicists and Well Log Analysts (SPWLA), and a Registered Professional Engineer with Alberta Professional Engineers, Geologists and Geophysicists (APEGGA).