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## Unlocking the Mystery of Formation Evaluation in the Hostile Conditions of the Krishna- Godavari Basin, India

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### Summary

Drilling and formation evaluation of deep wells in the Krishna- Godavari basin on the east coast of India has been very difficult due to the reservoirs' ultrahigh temperatures up to 405 degF [207.2 degC] and pressures upto 13000 psi [89.6 MPa]. Formation evaluation performed using only conventional logs like gamma ray, resistivity, density, and neutron may lead to incorrect determination of reservoir properties. The basin is also structurally complex. The complex faulted nature of the intersected formations cause stuck pipe, and loss of circulation, HPHT conditions, and the presence of overpressure zones attributed to the problem.

This paper presents an innovative and robust formation evaluation technique using wireline logs at HPHT conditions to optimize perforation and depth-interval selection. This new interpretation scheme uses the combination of elemental concentration from nuclear- capture spectroscopy logs along with HPHT well logging basket (standard neutron, density, and resistivity in HPHT) and sonic log measurements to get a reliable and accurate description of the lithology and matrix parameters. A critical log in the HPHT well logging basket was the epithermal neutron porosity suite, which aimed to overcome interpretation challenges in HPHT conditions.

**Keywords:** HPHT, Hostile condition, APS-Sigma-ECS-Sonic, Krishna Godavari basin, Drilling & Formation evaluation, mechanical earth model

### Introduction



Location of Study area (Courtesy: DGH India)

Wells in high-pressure, high-temperature (HPHT) conditions are always categorized as high-risk and expensive, and formation evaluation in the well poses challenges. However, the increasing energy demand in India, increases the drive for drilling wells in hostile conditions.

The Krishna-Godavari Basin is a proven petroliferous basin of continental margin located on the east coast of India. Its onland part covers an area of 5,791 mi<sup>2</sup> [15,000 km<sup>2</sup>], and the offshore part covers an area of 9,652 mi<sup>2</sup> [25,000 km<sup>2</sup>] with up to 10,763-ft [1,000-m] isobath. The basin contains 1.9-mi-thick [5-km-thick] sediments with several cycles of deposition, ranging in age from Late Carboniferous to Pleistocene.



Complex lithologies in the basin introduce new petrophysical challenges. Conventional wisdom or approaches to interpret wireline logs do not always deliver the desired accuracy in petrophysical responses. The potential of improved accuracy in lithology characterization and porosity evaluation led to the acquisition of nuclear spectroscopy along with the epithermal neutron porosity. However, the HPHT challenges could be overcome with suitable logging suite and modern technologies.

Two wells (Well A and Well B) were drilled and logged in HPHT condition. Keeping the targets and objectives in mind, the wells were explored and logged with a proprietary HPHT well logging suite along with sonic and elemental capture spectroscopy (ECS) tools in the openhole section. The accurate formation evaluation information (i.e., porosity, lithology, and water saturation) are essential for the precise evaluation of hydrocarbons in place; also, such information plays a vital role in perforation optimization strategies and the perforation depth intervals. An accelerator porosity sonde (APS) has delivered epithermal neutron porosity and sigma measurements in this HPHT environment. The ECS tool played a substantial role in our sigma log interpretation because it provided accurate lithology, clay-volume, grain-density, and matrix- sigma data. The permeability ( $k$ -Lambda) derived from ECS also provided a sense of permeability of the reservoir.

The acoustic slowness values were used to confirm the possible HC zones and compute accurate formation elastic moduli. In one well, dipole sonic data was acquired, which helped develop a mechanical earth model. The model provided a categorical description of the state of stress and relative rock strength for the stratigraphic section penetrated by the well.

### Logging Solution and Methodology

Wells completed in HPHT environments are inherently expensive undertakings. The risk associated with well evaluation and completion intensifies as borehole pressure and temperature rise. However, regardless of the danger and expense, the number of HPHT wells is increasing around the world.

Conventional tools cannot overcome the HPHT barrier. Their electronics fail because the temperature increases

inside the tool, dissipating the power consumption of the internal instruments. Using modern electronics and putting the tool electronics in a Dewar flask help to sustain the tool for acceptable logging time in hostile environments.

### APS-Sigma logging

In the APS tool (Fig.1) the neutron detectors are ecentered, borehole-shielded, and focused toward the formation, providing epithermal neutron porosity measurements that require only minimal environmental correction. The array detectors count epithermal neutrons, which contain hydrogen-index information. An electronic neutron source generates pulses of 14-MeV neutrons.

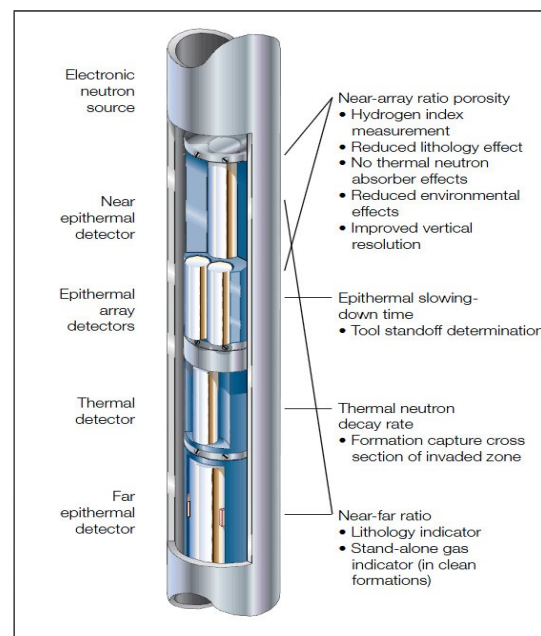


Fig.1 Accelerator Porosity Sonde

The neutron yield is large enough to allow detector shielding and epithermal neutron detection without loss of precision. Two porosity measurements are computed to effective formation grain density with different responses. One, based on the far-spaced detector signal, is similar to a conventional thermal neutron porosity measurement; the other, based on the medium-spaced detector signal, is almost insensitive to the formation grain density and is therefore directly related to the formation hydrogen index. Comparison of these two porosities is useful for lithology evaluation and gas detection. This measurement includes an estimate of



apparent standoff, which is used to correct the epithermal neutron porosity. Moreover, the thermal neutron decay rate provides a measurement of the formation capture cross section (sigma log).

### ECS logging

ECS techniques (Fig. 2) use a standard AmBe neutron source and a 3-in-diameter BGO crystal for measuring relative elemental yields based on neutron-induced capture gamma-ray spectroscopy. The primary elements measured with the ECS include: Si, Ca, Fe, S, Ti, Gd, Cl, and H. Lithology processing of spectra from neutron-induced gamma ray spectroscopy tools is a technique whereby the elements Si, C, and Fe can be used to create an accurate estimation of clay volume. Carbonate concentrations are determined from the calcium concentration log with an accuracy that is not available from any other logging devices. Anhydrite is determined from the calcium and sulfur logs. Finally, the remainder of the formation is composed of Q-F-M (quartz, feldspar, and mica) minerals.

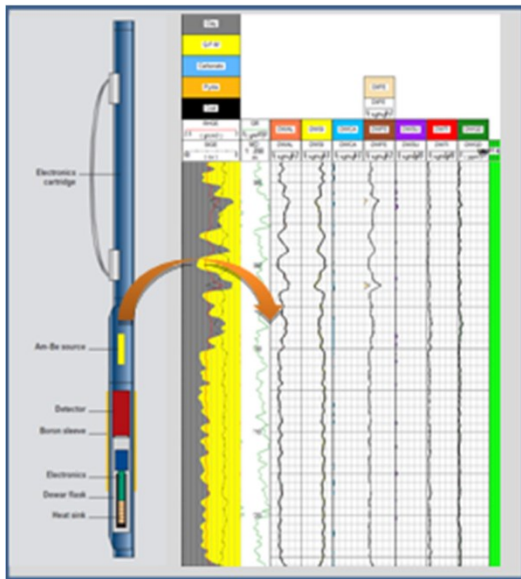


Fig.2 ECS tool and SpectroLith output result

Other algorithms are available for the computation of pyrite, siderite, coal, and salt. Matrix properties, including matrix density and matrix sigma, are also calculated from the dry-weight elemental concentrations. The main ECS petrophysical applications are quantitative lithology, grain density, and sigma matrix for accurate porosity and permeability.

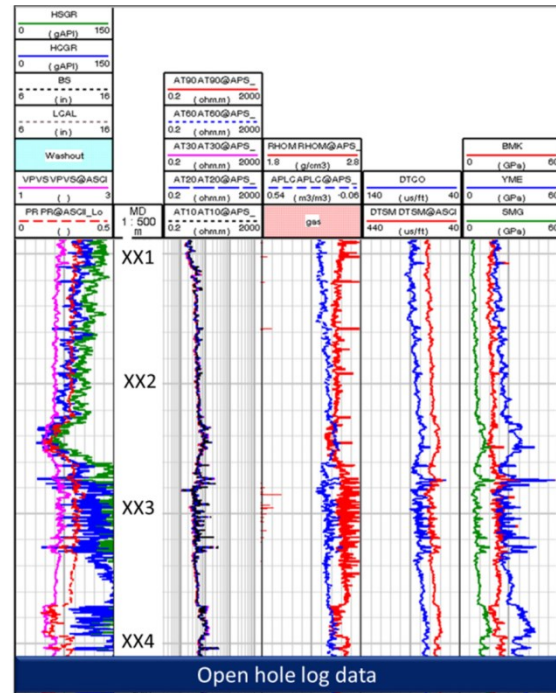


Fig.3 Open hole log data

Accurate formation evaluation can be attained by integrating the conventional logs along with APS-sigma and ECS logs over reservoir section, where all data were available. Using of advance log together with the conventional log help to achieve an accurate and robust petrophysical model through the ELAN interpretation technique.

This novel integrated interpretation technique for determination of accurate lithology, porosity and gas saturation in HPHT conditions identified the most promising hydrocarbon-bearing zones.

These wells encompass the major hydrocarbon zones in this Krishna-Godavari shallow water block and in similar HPHT conditions and geological structures in India.

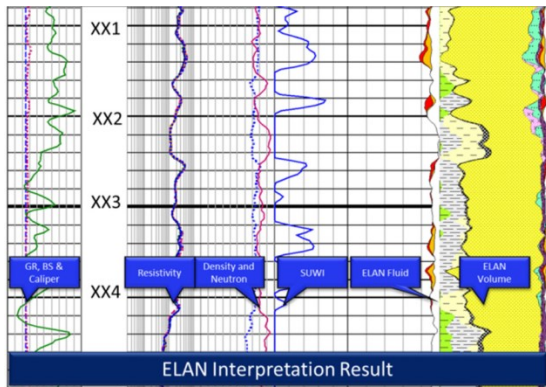


Fig.4 ELAN Interpretation result; integrating conventional and advance open-hole log data

### Dipole Shear Sonic

With monopole sonic measurements, shear slowness could only be recorded in fast formations, in which the wave in the formation is faster than the compressional wave in the mud. This limitation was removed with the commercial introduction of dipole shear logging in HPHT conditions up to 400 degF [204.4 degC]. Trends have been identified on  $V_p/V_s$  versus Delta-t Compressional (DtC) crossplots for all lithology types, in particular in unconsolidated shaly sands sequences. In unconsolidated sands, the presence of gas in the rock is known to have a strong influence on acoustic slownesses. The  $V_p/V_s$  ratio is often used qualitatively to detect the presence of gas from sonic logs. Dipole shear sonic log acquired in Well A indicated the presence of gas (Fig. 3).

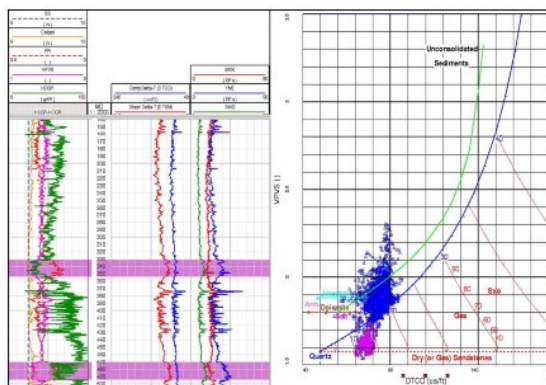


Fig.5 DSI output and DTC vs.  $V_p/V_s$  crossplot indicating presence of gas

Moreover, using all the available logs (i.e., dipole sonic, density, APS, elemental analysis volumes, and the

drilling data), we developed a mechanical earth model, which is an explicit description of the state of stress and relative rock strength for the stratigraphic section penetrated by Well A.

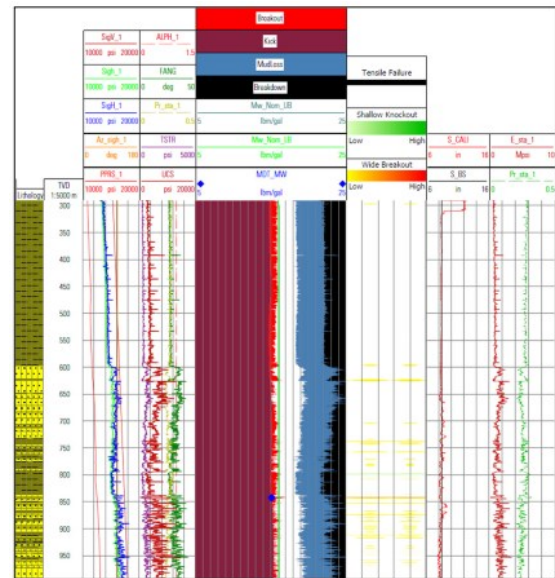


Fig.6 Post-drill 1D mechanical earth model

The model captured the most important geomechanical data relevant to well construction and wellbore instability management for the rest of the field. The post-drill 1D mechanical earth model (Fig. 4) was then used for drilling new wells around the proposed platform. This was achieved by determination of safe and stable mud-weight envelopes at varying borehole azimuth and inclination and drill bit selection optimization.

### Results

This integrated log interpretation technique customized for determining accurate lithology, porosity, and gas saturation in HPHT conditions, identified the most promising hydrocarbon bearing zones of the wells (Fig. 5). Thus, the robust methodology proved invaluable in determining pay zone in this HPHT condition. These advanced processing techniques imparted the robustness to the formation evaluation in addition to the conventional method. The sonic data from Well A was further used to build a postdrill 1D mechanical earth model, which helped to drill subsequent wells in the hostile condition.

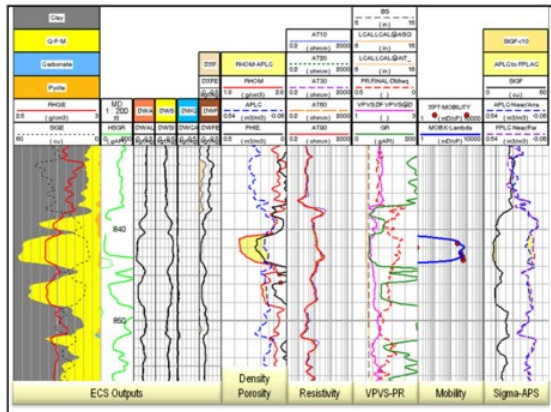


Fig.7 APS & ECS added another dimension to the formation evaluation and gas identification

## Conclusion

Petrophysical evaluation at such hostile temperature and pressure ranges has been demonstrated to provide accurate results. Application of standalone conventional logs used for formation evaluation of the complex wells may not achieve the exactitude sought. A novel HPHT well logging platform for determining accurate lithology, porosity, and gas saturation identified the most promising hydrocarbon-bearing zones. The dipole shear sonic data was used for generating the 1D mechanical earth models.

The HPHT environment required the review of drilling equipment and procedures to continue the exploration program. The success of these wells is attributed to innovative, fit-for-purpose drilling and formation evaluation practices, rigorous pre-drill planning and synergy among the multidiscipline team. As the search for oil and gas leads to deeper reservoirs, HPHT conditions have become key considerations in drilling operations and reservoir evaluation and development. Innovative technologies and solutions should be used to meet the challenges of drilling, evaluating, and completing HPHT wells and developing these fields.

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