[PS]Role of Clay Diagenesis in Hydrocarbon Accumulation in Shale Reservoirs of Sanand Field, Cambay Basin, Gujarat, India: A Case Study*

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Abstract

The lower Eocene (Ypresian) Chhatral Member in Sanand Field is located in the western part of Ahmedabad Sub-Block in Cambay Basin, India (Figure 1). It has a number of pay zones developed within thick carbonaceous and sideritic shale. The pay zones are very thin, heterogeneous and developed as discontinuous laminations and lenses. A number of conventional cores were studied from the Chhatral Member to understand the nature of lithofacies and their reservoir characteristics (Figure 2). However, predominance of shale and very high fissility often masked the identification of reservoir facies. The detection and evaluation of these reservoirs is also difficult with wireline logs as the overall resistivity of shale is very low (1-2 Ωm) and there are no significant variations in resistivity, Density-Neutron and GR-SP logs response against the hydrocarbon bearing and non-hydrocarbon bearing intervals. Conventional wire line log signatures are usually suppressed, and therefore their utilization as interpretation tools becomes less effective, especially in calculation of net pay thickness for reserve calculation. Presence of hydrocarbon in the shale is normally established only by observing oil while drilling through the zone. The shale is dark grey and highly fissile having average TOC 3.0% and is immature to early mature with VRo 0.44 to 0.55. The shale has been deposited over a wide spread tidal flat and contains kaolinite and chlorite as most abundant clay minerals.

Representative conventional cores from six wells, Sanand "A", "B", "C", "D", "E" and "F" in the Sanand Field were taken for the study. Detailed lithofacies and microfacies analysis, X-ray diffractometry and SEM studies were carried out to demarcate thin lithological heterogeneity within the shale and post-depositional diagenetic changes. The core-plug data were used for the characterization of the reservoir units by determining Effective Porosity (Φ_e), Air Permeability (Ka), Grain and Bulk Density (gm/cc) parameters, and MICP (Mercury Injection Capillary Pressure) studies were made for direct assessment of pore geometry of the rock and the irreducible water saturation (S_{irw}) which indicates the amount of connected pore space that is available to hydrocarbons (1- S_{irw}). The petrophysical attributes were used to segregate the reservoir facies from the non-reservoirs (Figure 3). Rock-Eval pyrolysis was also carried out in Sanand "A" and

"F" wells to detect the presence of migratory/accumulated hydrocarbons and petroleum generative potential of rock samples (S1 and S2) and the nature of hydrocarbons present with Pyrolysis Gas Chromatograph.

The Chhatral Member underlies the sandstone-coal facies of the middle Eocene Kalol Formation and is underlain by silty and argillaceous facies of lower Eocene Mehsana/Sobhasan Member of the Kadi Formation. It mainly consists of dark grey, feebly calcareous, carbonaceous shale with occasional siderite which is developed as thick bands, nodules, lenses and disseminations in the matrix. The carbonaceous shale in the Sanand Field is highly fissile and very rich in organic matter having average TOC 3.0%, HI 130mgHC/gmTOC, very poor SPI (<1.0MT of HC/m2) and is immature to early mature with VRo -0.44 to 0.55. The shale in the area has been deposited over a widespread tidal flat and belongs to Early Eocene TST.

Mechanism and Reservoir Development

The Chhatral Member has a number of thin (10-25cm), laterally discontinuous and irregular reservoir facies comprising silty to very fine grained clay pellets/nodules of chlorite and kaolinite developed within the shale. Kaolinite is the most abundant clay mineral in the silty portion and has been identified in thin-section by its crystal morphology, color, and low birefringence and also by using X-ray diffraction and SEM. The kaolinite occurs as very fine to fine grained floating grains in argillaceous and partially ferruginised sideritic matrix and has better intergranular porosity. The other constituents include authigenic quartz, chlorite, disseminated pyrite and carbonized plant remains.

The petrographic studies indicate that most of the chlorite is transformed into kaolinite pseudomorphs. In the first phase, the diagenetic chlorite was formed in the argillaceous matrix in an alkaline milieu (Reineck and Singh, 1980). In the second phase, the diagenetic transformation of chlorite into vermiculite and finally to kaolinite took place in an acidic milieu. The transformation of chlorite into kaolinite is the characteristic diagenetic events that the shale has undergone. The kaolinite pseudomorphs are light green coloured and exhibit various stages of transformation. The kaolinite and chlorite pellets are floating in partly ferruginised argillaceous matrix (Figure 4). The diagenetic clay pellets define the framework texture and qualify as an unconventional reservoir developed insitu within the shale at selected intervals under favourable physio-chemical conditions. The alteration of chlorite to vermiculite was characterized by the loss of Mg and Fe and minor Al from the brucite-like sheet of chlorite (Grim, 1968). The Fe released during the alteration of vermiculite to kaolinite is likely to migrate to micropores and intergranular space to form goethite (Aspandiar et al., 2002). The quality of the reservoir is defined by the degree of transformation of chlorite into more stable kaolinite.

Textural heterogeneity at the meso and micro levels is the main cause of formation of the reservoir capacity of clayey/argillaceous reservoir (Klubova, 1988). The transformation and stability of kaolinite in acidic conditions, and precipitation of calcite and siderite in alkaline conditions (pH 8.4) indicate a fluctuating pH in the basin, which might have facilitated both creation and destruction of porosity at certain intervals. Prevalence of acidic pH conditions in the basin could have been caused by release of carbonic acids during diagenetic transformation of organic matter in the shale. A clear inhomogeneity in the Chhatral shale has been observed and the reservoir facies thus developed normally has thickness less than the resolution capability of the Induction logs.

Petrophysical Characteristics of the Reservoir Facies

The geometric mean porosity of the cores ranges from 11% to 20%; the permeability has a range of 0.1 to 15.3 md. Capillary pressure studies indicate a bimodal connected pore sub-system, comprising micropores largely or completely saturated with high capillary bound (or irreducible) water and a coexisting system of larger pores which may have high hydrocarbon saturation. The pore geometry is largely fabricated by micro-pores and the pore aperture radii are small. The Pore Throat Sorting (PTS) and Pore Size Distribution (PDS) pattern suggests a moderate sorting (PTS=1.54-2.57) and dominance of micropores of less than 1 µm size. The rock fabric is dominantly fabricated by micro pores of dia <1 µm, have a high capillarity and high irreducible water saturation (S_{irw}) ranging from 35% to 84%. About 2% to 19% of the pores are of larger diameter (1 µm to 25 µm), have larger pore aperture radii and smaller displacement pressure and normally belong to the diagenetically formed reservoir units as discussed above, having better flowing characteristics and pore geometry.

Geochemical Characteristics of the Chhatral Member Reservoir Facies

Rock-Eval pyrolysis was carried out to detect the presence of migratory/accumulated hydrocarbons and petroleum generative potential of rock samples (S1 and S2). Two core samples from the Sanand “A” well, which indicated presence of hydrocarbon from Rock-Eval screening techniques are further studied with Pyrolysis Gas Chromatograph to determine the nature of hydrocarbons. Both the free hydrocarbons present in a sample and those generated by pyrolysis of kerogen and heavy extractable compounds such as resins and asphaltenes are subjected to gas chromatography, yielding detailed chromatographic spectra of S1 and S2 peaks. The Rock-Eval parameters indicate that the two samples have high S1 values (1.29 - 5.99 mg/g rock) and (13.39 - 3.52mg/g rock) and high PI (0.49 - 0.89) and (0.72 - 0.53) respectively, which is indicative of hydrocarbon accumulation in the zones. Two additional core segments from Sanand “E” well, indicate an S1 value of 1.19-0.83mg/g rock, S2 value of 2.21-4.89 mg/g rock and 0.35-0.15 PI. Diagenetic reservoir facies have been observed against this zone. Thermal extracts of the two samples from the Sanand “A” well show normal distribution pattern without any signature of biodegradation, and their fingerprints match exactly with same genetic attributes. Thermograms also show wide spread of hydrocarbons with higher concentration in the C27-C31 range. Both thermogram patterns are different from their respective pyrograms, which indicate that the hydrocarbons present in the Chhatral shale are of migratory nature and not generated insitu.

Possible Causes of Low Resistivity in Chhatral Pay

The petrophysical studies have established that the low resistivity in Chhatral Member is an artifact of pore geometry. The micropore system with high capillary bound (or irreducible) water in the shale does not easily de-saturate and maintains high conductivity over the macropore system in diagenetic reservoirs having a variable conductivity depending on the hydrocarbon saturation, since the electric currents flowing through the micropores bypass the restrictive hydrocarbon bearing macropores. A large amount of dispersed clay may also have provided additional conductive pathways through the cation-exchange mechanism.

The electrical resistivity studies and the capillary pressure studies suggest that the behavior of the rocks is non-Archie. Any depositional or digenetic environment which produces a rock fabric with a continuously connected system of small pores in addition to larger pores connected by proportionally large pore throats can result in low resistivity pay. In these types of bi- or poly-modal pore systems the capillary properties of the continuous systems of smaller pores results in a connected pore sub-system which is largely or completely water saturated and has high capillary bound (irreducible) water. A coexisting system of larger pores may contain high hydrocarbon saturation. The electrical effect of a dual pore system is that the macropore system may have a variable conductivity depending on the hydrocarbon saturation; the micro pore system does not easily de-saturate and maintains high conductivity as a result, regardless of high hydrocarbon saturation, and the rock remains conductive since the electric currents flowing through the micro pores bypass the restrictive hydrocarbon bearing macro pores. This is supported by the capillary pressure studies which suggest that the rock fabric is dominanted by micro pores of dia >1 µm, has a high capillarity and high irreducible water saturation, and at the same time about 2% to 19% of the pores are of larger diameter (1 µm to 25 µm), larger pore aperture radii and smaller displacement pressure.

Taking the lead from the above findings, a novel method of using the Resistivity Image Data was made in the Sanand “A” well, in conjunction with other logs by Rao et al. (2007), in order to assess the potential of the Chhatral Member in terms of pay thickness, effective porosity, and oil saturation for quantitative evaluation of the entire Chhatral Member. In view of the dispersed nature of the heterogeneous reservoir, high resolution Scaled Synthetic Resistivity (SRES) curves were generated by processing the image data (Figure 5). The study indicates the presence of high resistivity thin layers in otherwise homogeneous reservoir; corresponding to diagenetically formed reservoirs in shale. The reservoir heterogeneity/anisotropy are found to be responsible for masking the average scaled resistivity response in characterizing the thin layers, which makes their identification very difficult on conventional resistivity logs.

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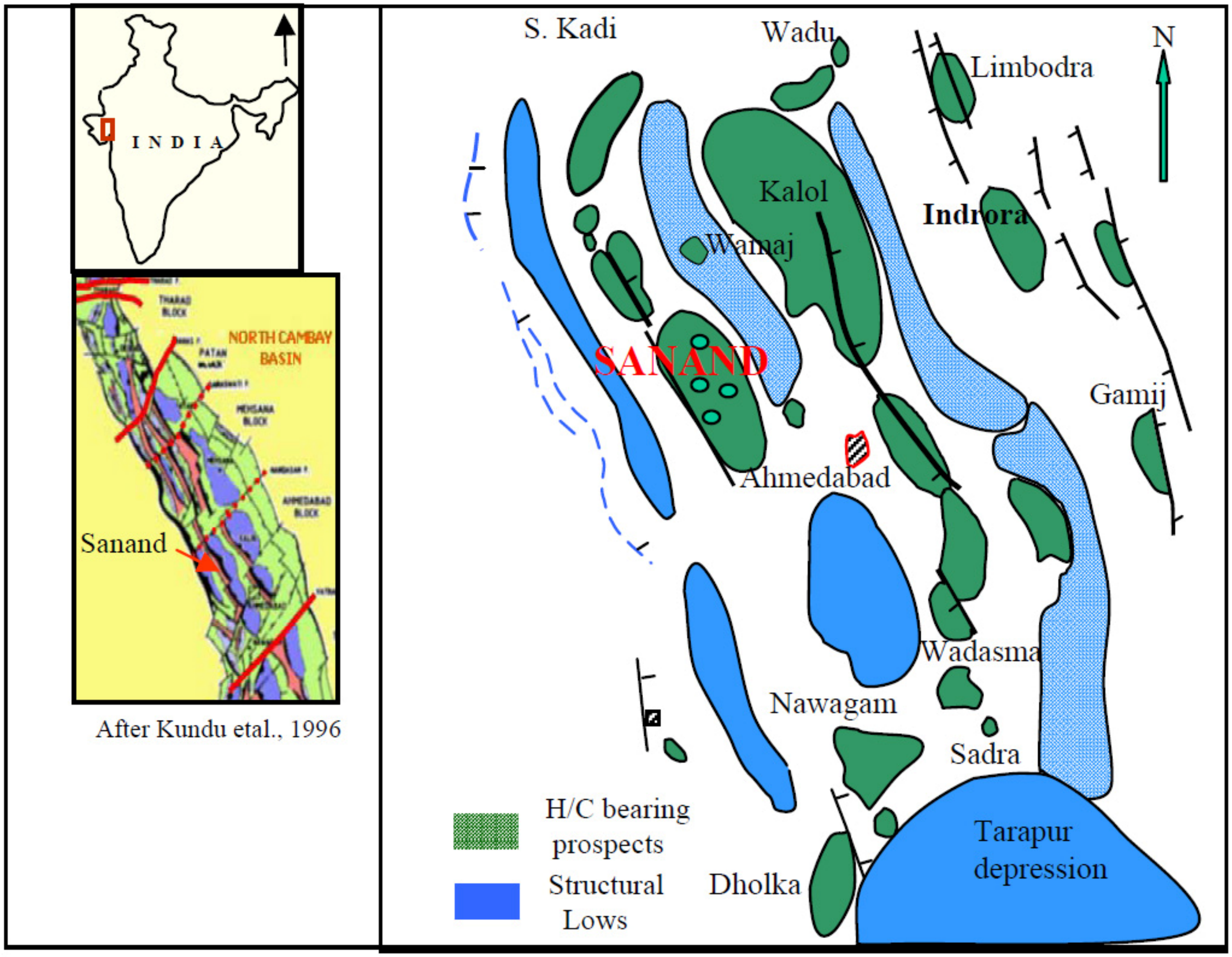

Figure 1. Tectonic map of Cambay Basin and location map showing Sanand Field.

Figure 2. Core photographs of selected segments in Core #2 and Core #3 in Sanand "A" well, showing development of reservoir facies. Left two cores: Core # 2 (1340-1349m); Right three cores: Core # 3 (1349-1358m).

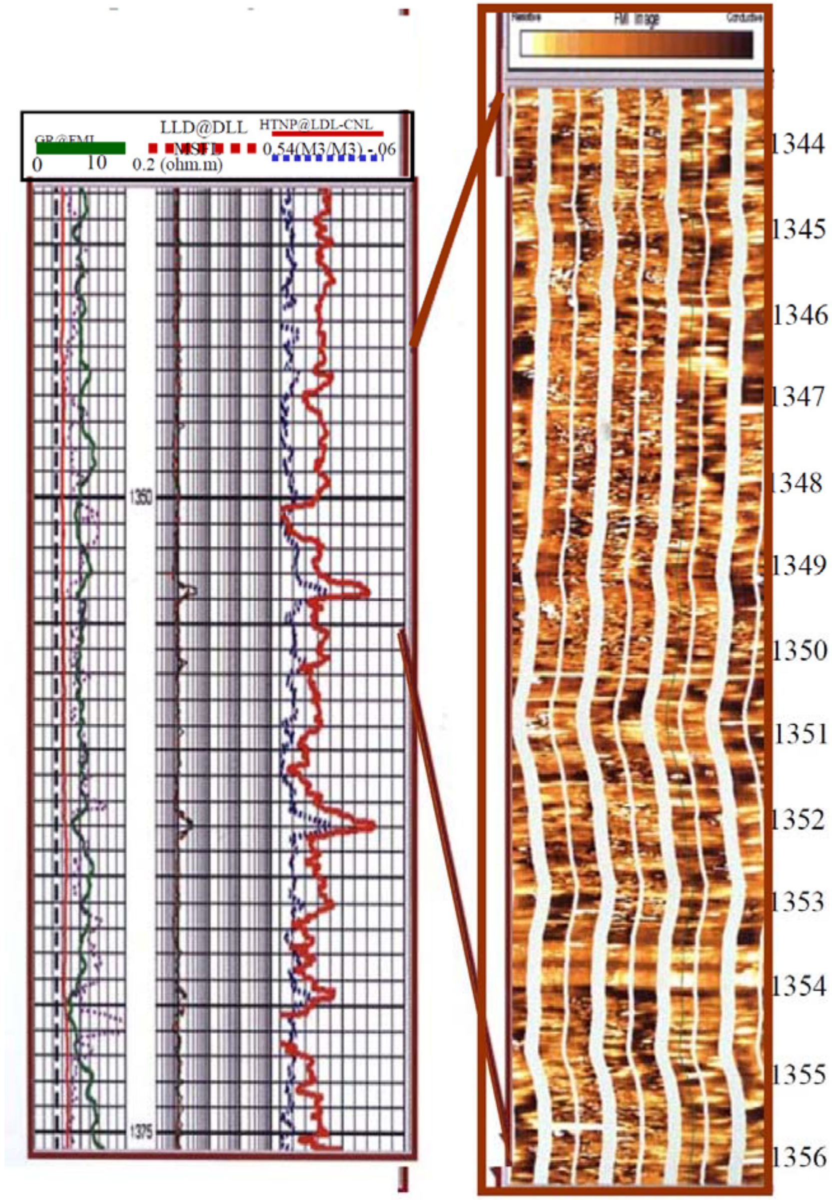

Figure 3. Logs in Sanand "A" well showing heterogeneity of lithofacies in Chhatral Member; FMI log shows isolated occurrences of reservoir facies.

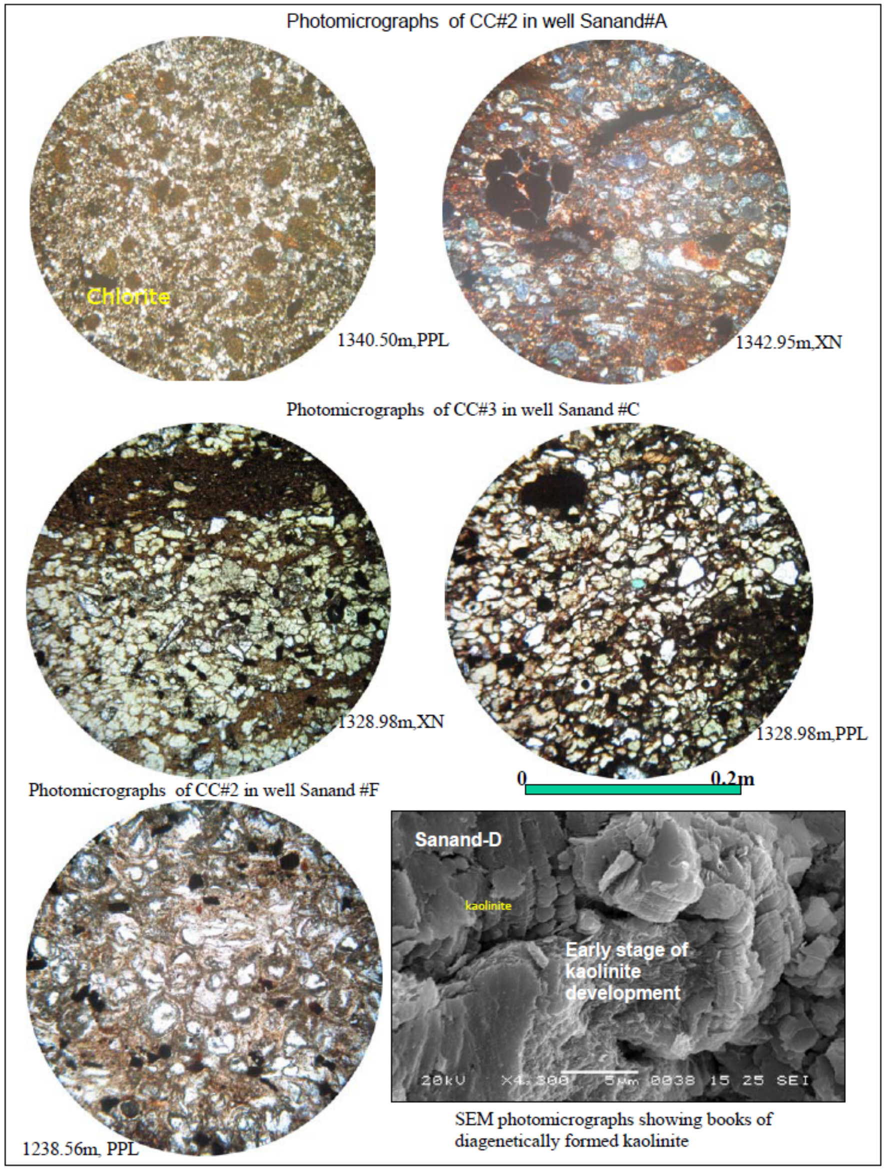

Figure 4. Photomicrographs of selected core segments in shale showing diagenetically formed kaolinite pellets and chlorites. All photomicrographs have same magnification. Lower right: SEM photomicrograph showing books of diagenetically formed kaolinite

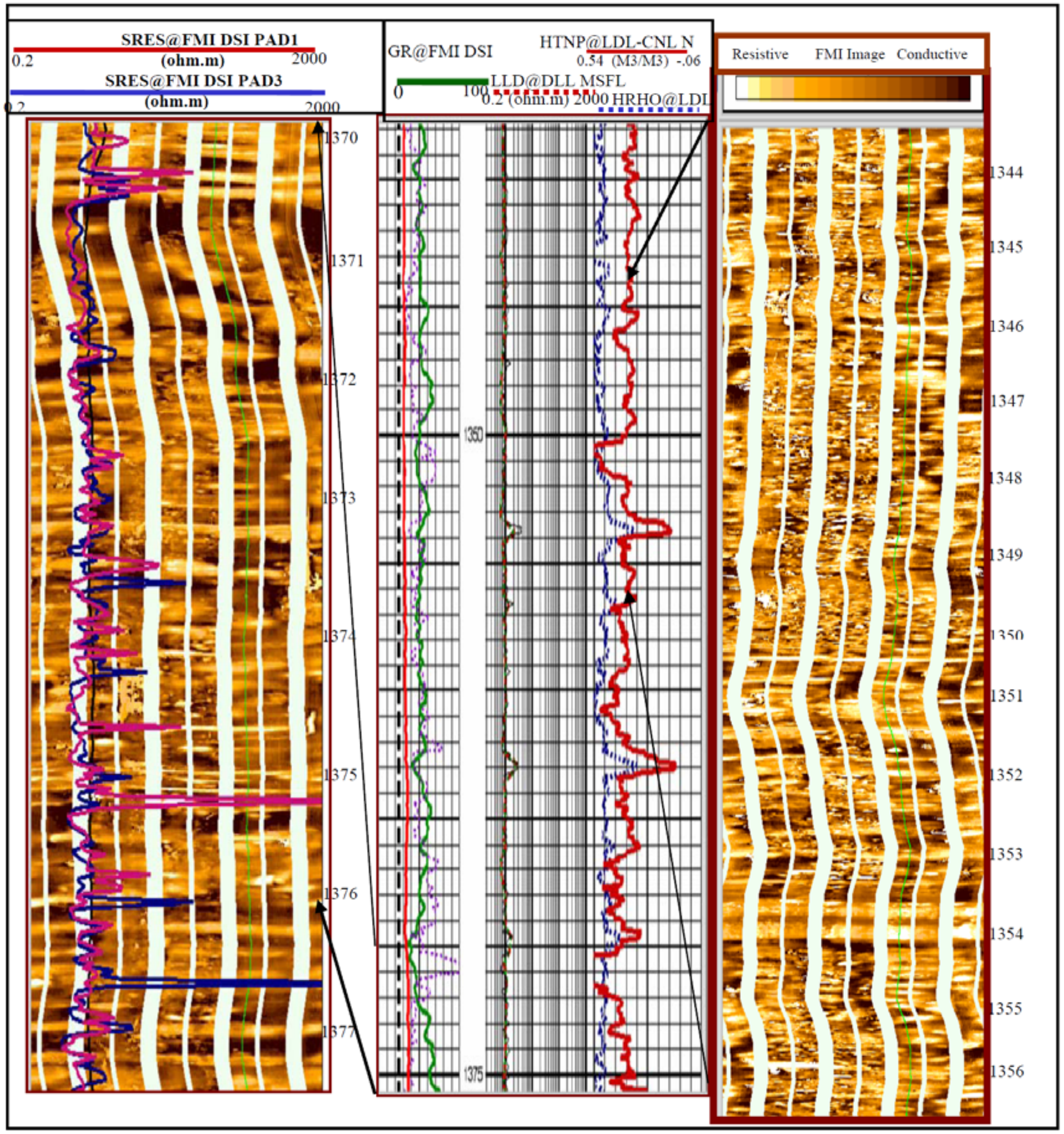

Figure 5. SRES curves generated by processing image data, wherein FMI tool current is calibrated with Medium Lateral Resistivity curves recorded in the same interval to obtain measurement. Figure shows two such measurements against two pads and variations in resistivity due to heterogeneous development of reservoir facies in Sanand “A”.