

SANDWICH: LOG EVALUATION IN LAMINATED SHALY SANDS

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SUMMARY

Formation evaluation from well logs in laminated shaly sands has often suffered from lack of proper models, and in many cases led to underestimation of oil or gas in place. Shell Research have developed a technique that allows consistent analysis of formations with laminated, dispersed and structural shale, leading to better quantification of oil and gas volumes in place. Present research is concentrating on further calibration of the model input parameters by core and high-resolution logs such as borehole imaging logs.

The present paper shows results of application of the model to the oil fields in Sarawak Shell Berhad (SSB) in Malaysia. The results show increases in the hydrocarbon volumes of up to 40%, as compared to the previous conventional analysis. Higher increases were obtained in environments with higher amount of laminated shale. The main benefit of application of the SANDWICH model was the increased confidence in the volumes of oil and gas in place in laminated shaly sands. This was achieved through reduction of the uncertainty in the log derived inputs to volumetrics. As a result, the reduced uncertainty has helped to reconcile reservoir production with oil in place, and it will improve further development planning such as re-developments and re-completions.

INTRODUCTION

Evaluation of oil and gas volumes in thinly laminated shaly sand reservoirs traditionally has been hampered by the lack of appropriate models for well log evaluation. The laminations often have been too thin to be individually resolved by the logs. Then, the logs have represented an average of the log values over the shale and sand layers within the resolution of each log. Since this was not a linear average for resistivity logs, evaluations usually resulted in underestimates of the hydrocarbon saturation, or in hydrocarbons being

missed. This underestimation was known but could seldom be quantified.

The existing shaly sand log evaluation models such as the Waxman-Smits model (Ref. 1) or the Dual Water model (Ref. 2) were developed for the situation of dispersed shale, with clay particles resident in the pores of the sand matrix. In laminated sand/shale, this is not true, and the behaviour of the logs is different, especially for the resistivity logs (Ref. 3). As a result, use of the Waxman-Smits or similar techniques may lead to under- or overestimates in hydrocarbon saturation. This was observed for example in lower calculated hydrocarbon saturations than those observed in capillary pressure curves. This has left a considerable uncertainty and often an underestimate of the oil and gas in place.

Shell Research have developed a technique that allows consistent analysis of formations with laminated, dispersed and structural shale, leading to better quantification of oil and gas volumes in place. The resulting SANDWICH model was introduced to Shell Operating Companies in 1993, and increasingly applied in 1994 and 1995. Present research is concentrating on further calibration of the model input parameters by core and high-resolution logs such as borehole imaging logs.

An accurate determination of the volumes of oil and gas in place early in the exploration and appraisal phases will lead to a development properly sized to the reserves. The impact of reduction in the uncertainty in oil or gas in place on the development planning is of the order of tens of millions of dollars, through correct numbers of wells and platforms. In producing fields, a reduction in the uncertainty in volumes would help in reconciling reservoir production with oil in place, and would improve further development planning such as re-developments and re-completions.

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THE SANDWICH MODEL

The SANDWICH model (SAND With Intercalating Clay and Hydrocarbons) was developed in Shell Research specifically to deal with the environment of laminated sand/shale. The model was distributed to Shell's Operating Companies in the form of a module inserted into the general well log evaluation package.

The approach of the SANDWICH model is to accept that the logs represent an average over the sand and shale log values, rather than trying to resolve the laminae individually. From these average values, sand and shale fractions and fluid contents are derived.

First the shale laminations are separated from the sand laminations, then log values are derived for the sand laminae, and finally porosity and hydrocarbon saturation are calculated in the sand laminae using these logs. An additional step in the computer program allows estimating uncertainties in the results by the Monte Carlo technique.

Fig. 1 schematically shows this concept. At each depth increment (usually 0.5 ft), the formation is assumed to consist of a single shale lamination and a single sand layer. In this way, all shale laminations seen by the logging tools positioned at that depth are treated as a single layer, and all sand laminations as one sand layer. The single sand layer is assumed to contain the sand matrix, dispersed and structural shale, and porosity containing the fluids. The effects of the laminated shale on the logs are treated explicitly, and porosity and hydrocarbon saturation are determined for the sand laminae.

The vertical resolution of the logging tools is not 0.5 ft, hence in general the logs represent an average over a wider interval. Also, resolutions differ considerably, for example from 1.5 ft for a density log to 6 ft or more for an induction log. Therefore, before applying the SANDWICH model, the logs are brought to the same resolution, either by averaging the higher resolution logs or by deconvolution of the lower resolution logs.

The SANDWICH program essentially consists of four steps (see Fig. 2). Firstly, sand and shale fractions and sand porosity are derived. Density and neutron logs can be used to derive the sand and shale fractions, for example using the Thomas-Stieber model (Ref. 4) including an iterative application of SANDWICH to correct these logs for hydrocarbon effects. Alternatively, a shale fraction can be derived from other conventional logs such as the gamma ray log or from high-resolution logs such as dipmeter or borehole image logs. Subsequently, the porosity in the sand

layers is derived from the sand and shale fractions and the density and neutron log.

In the second step, log values for the sand layer are derived from the measured logs and the sand, shale and porosity volume fractions from the previous step. Sand layer resistivity is calculated from the resistivity log by models which incorporate the mixing of sand and shale resistivity at a certain apparent dip angle between borehole and formation layers. Resistivity anisotropy of the sand and shale layers is also taken into account.

In the third step, the hydrocarbon saturation in the sand layer is calculated from the log values for the sand layer. Various models can be used here, as in general this sand layer is relatively clean because the laminated shales have already been taken out.

In the final step, uncertainty levels in the output values are determined by the Monte Carlo technique. Uncertainty in the results such as hydrocarbon saturation is obtained by varying the input parameters and log values based on the known or estimated uncertainty in each of these. The resulting minimum and maximum represent the one-standard deviation calculation uncertainty. Geological and data scarcity uncertainties have to be added to these.

EXAMPLE WELL 1: OIL WELL

Fig. 3 shows a core photograph from a well in an oil field with laminated shaly sands. The geological environment is a coastal plain, with cycles of bay-type deposits overlain by tidal or estuarine channel and mudflat deposits.

In the figure, a large number of thin sand and shale laminations are observed. In general, in this reservoir, the layer thicknesses range from a few mm to a few m. It is clear from the figure, that even the highest resolution logs measure values that are averages over several laminations. Besides the laminated shale, some dispersed shale is present in the reservoir, as noted from geological description of the core.

Fig. 4 gives an example of a SANDWICH evaluation result for a well in the same field and in the same geological reservoir. Tracks 1, 2 and 3 show the raw well logs: gamma ray (GR), calliper (CALI), deep resistivity (LL9D), density (DENS) and neutron (CNL). Track 4 shows the volume fractions as calculated by SANDWICH, cumulatively from left to right laminated shale (V_{lam}), dispersed and structural shale (V_{shale}), sand matrix and the fluids, water and oil. Tracks 5 and 6 show the porosity and the oil saturation in the sand layers (Phi-sd and Sh-sd respectively), and compare these to the results from the

previous Waxman-Smiths evaluation (Phi-WS and Sh-WS). Track 7 shows the uncertainty (one standard deviation) in the oil saturation S_h , as calculated by the Monte Carlo option in SANDWICH. Track 8 shows a comparison of the equivalent hydrocarbon column ($EHC = Net \times porosity \times S_h$) at each depth, again compared to the previous results. The reservoir indicator in Track 8 shows the depth intervals where the SANDWICH results have been included in the volumetrics.

As observed in the figure, the SANDWICH analysis has been carried out over the entire interval. In previous techniques, no evaluation was normally carried out in intervals labelled non-reservoir, since the models did not apply. The laminated sand/shale model provides a useful reservoir description up to high shaliness levels, as long as the majority of the shale is laminated in nature. Evaluation at higher shaliness levels is required in laminated shaly sands, because the sand laminae can have good reservoir quality at high bulk shaliness, by mixing of thin layers of good sand with thicker layers of shale.

It is observed in the figure that the shale is mostly laminated in nature. This is partly caused by choice of the model input parameters to reflect the core description, and partly by the assumptions inherent in the model.

A reservoir cut-off on V_{shale} was used to distinguish reservoir from non-reservoir. Such a reservoir cut-off should be derived from core analysis, to distinguish between productive and non-productive reservoir. Logs are less suitable, because the logs respond more to the sand/shale mixing than to reservoir quality. High-resolution logs help to calibrate the shale and sand fractions, but are not very sensitive to reservoir quality in (more resistive) sand laminae. An other important point to consider in defining reservoir cut-offs is the lateral connectivity of the thin sand layers. These may or may not form part of an extensively connected reservoir.

At higher levels of shaliness the outcome of the SANDWICH model is less accurate, as observed from the Monte Carlo uncertainty in the oil saturation. The results become more sensitive to the uncertainties in the log values and in the chosen parameters. This is a consequence of the fact that at high shaliness, the logs are mainly responding to shale and hardly to the small presence of sand laminae. Hence, a very small error in a shale parameter or small scatter in the logs can cause large variations in the calculated oil saturation. A large

change in the properties of the sand layer is required to correct for a small variations in the shale parameters or in the logs.

EXAMPLE WELL 2: CORED WELL

Fig. 5 shows results in a cored well. In track 4, the shale fraction from core analysis is shown by the blocky line. A good qualitative but only a fair quantitative agreement is observed between the shale fractions from SANDWICH and those from the core description. In general, in the various fields, good results were obtained in some cases, meagre in others. The meagre results were attributed mainly to inaccuracy in the core description. In the past, less attention was paid to determination of accurate laminated shale fractions from core, because these were not used quantitatively.

In track 6, a comparison has been made of the SANDWICH oil saturations with those derived from capillary pressure measurements and with the Waxman-Smiths technique. The cap curve saturations are represented by a shaded band, derived from the range in measured saturations depending on porosity and cap curve measurement technique (mercury/air and air/brine). The SANDWICH results correspond much better to the capillary pressure results than did the Waxman-Smiths results, especially in the reservoirs below 170 m. In these thicker but laminated reservoirs, the SANDWICH saturations plot just below the cap curve band, suggesting that in this case the technique may still slightly undercorrect for the effects of the laminated shale. In the shallower thinner sands, e.g. at 146 m, the correspondence is less good, which is mainly attributed to wash-outs. This example clearly illustrates the underestimate in oil volume that can be made due to application of a dispersed shale model to logs from a laminated shale environment.

EXAMPLE WELL 3: GAS WELL

Fig. 6 shows a Formation Microresistivity Imager (FMI) borehole image log in a gas-bearing well in a turbidite, showing the highly laminated nature of the formation. Fig. 7 shows the results of SANDWICH application across the same interval. Here, a laminated shale indicator had to be derived from the gamma ray log, because neutron/density shale indicators were overshadowed by gas effects. In the SANDWICH analysis, the reservoir was assumed to consist of clean sand and pure shale.

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A large increase in gas saturation is obtained by introduction of the SANDWICH method. The dependence of gas saturation on shaliness has decreased but not fully disappeared, again suggesting a possible slight undercorrection for the laminated shale effects. In a turbidite, if sand quality would be independent of shaliness, one would expect gas saturation to be constant, except for in the transition zone.

Core analysis will be used to further calibrate and constrain the log evaluation results in similar wells in gas-bearing turbidites.

GENERAL OBSERVATIONS

Fig. 8 shows that a relationship exists in some fields between the level of laminated shale and the increase in equivalent hydrocarbon column (EHC) from application of SANDWICH. The more laminated shale, the higher the increase. This suggests that the more laminated shale is present, the more necessary it is to analyse the logs with a laminated shale model, and the more erroneous the assumption of "dispersed shale".

CONCLUSIONS

The Shell developed SANDWICH computer program has enabled a proper log evaluation in laminated shaly sands. The known underestimate and the uncertainty in the volumetrics in laminated shaly sands due to log-derived parameters have been reduced. Application in fields by Sarawak Shell has resulted in significant increases of up to 40% in the equivalent hydrocarbon column.

Calibration of the input parameters is important, especially those determining the sand and shale fractions. In addition, an integrated approach is required to distinguish productive reservoir, through core description, core measurements, high-resolution logs, well log formation tests and well tests. Further research is ongoing to establish methods for such integrated analysis and calibration.

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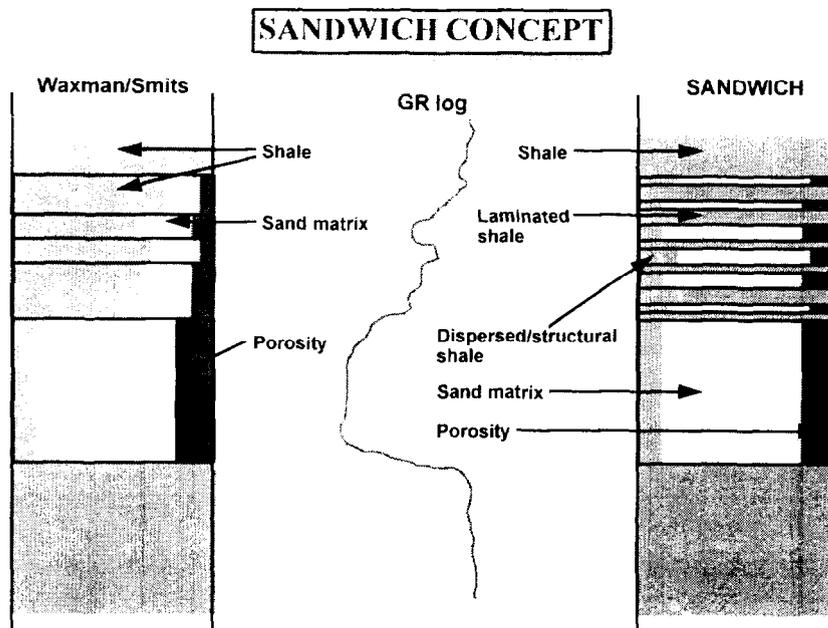


Fig. 1. SANDWICH concept of a laminated sand/shale sequence, and comparison with Waxman/Smits model.

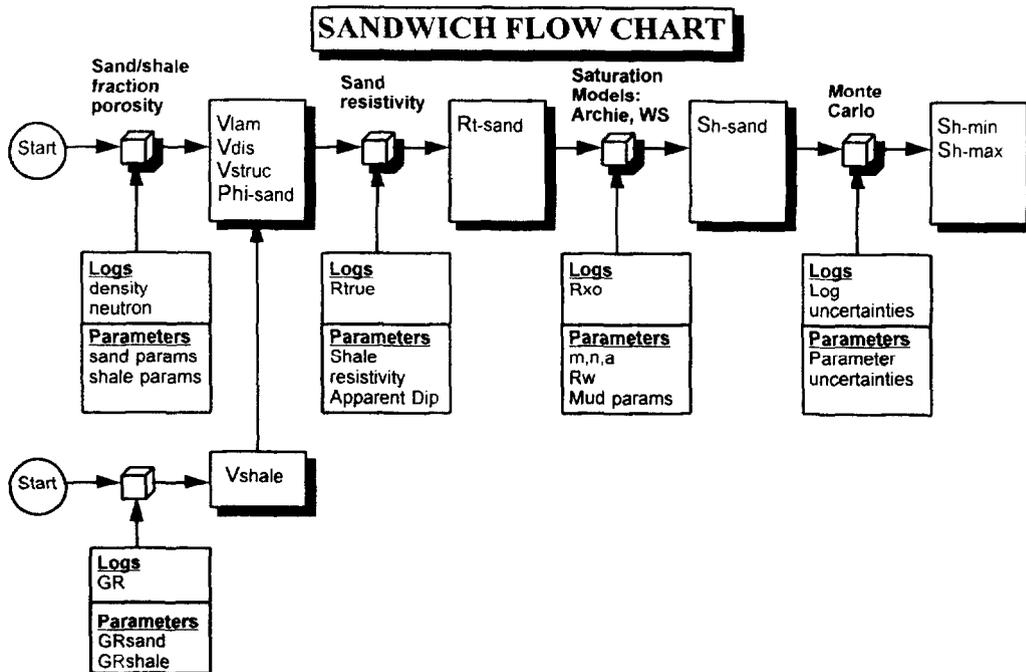
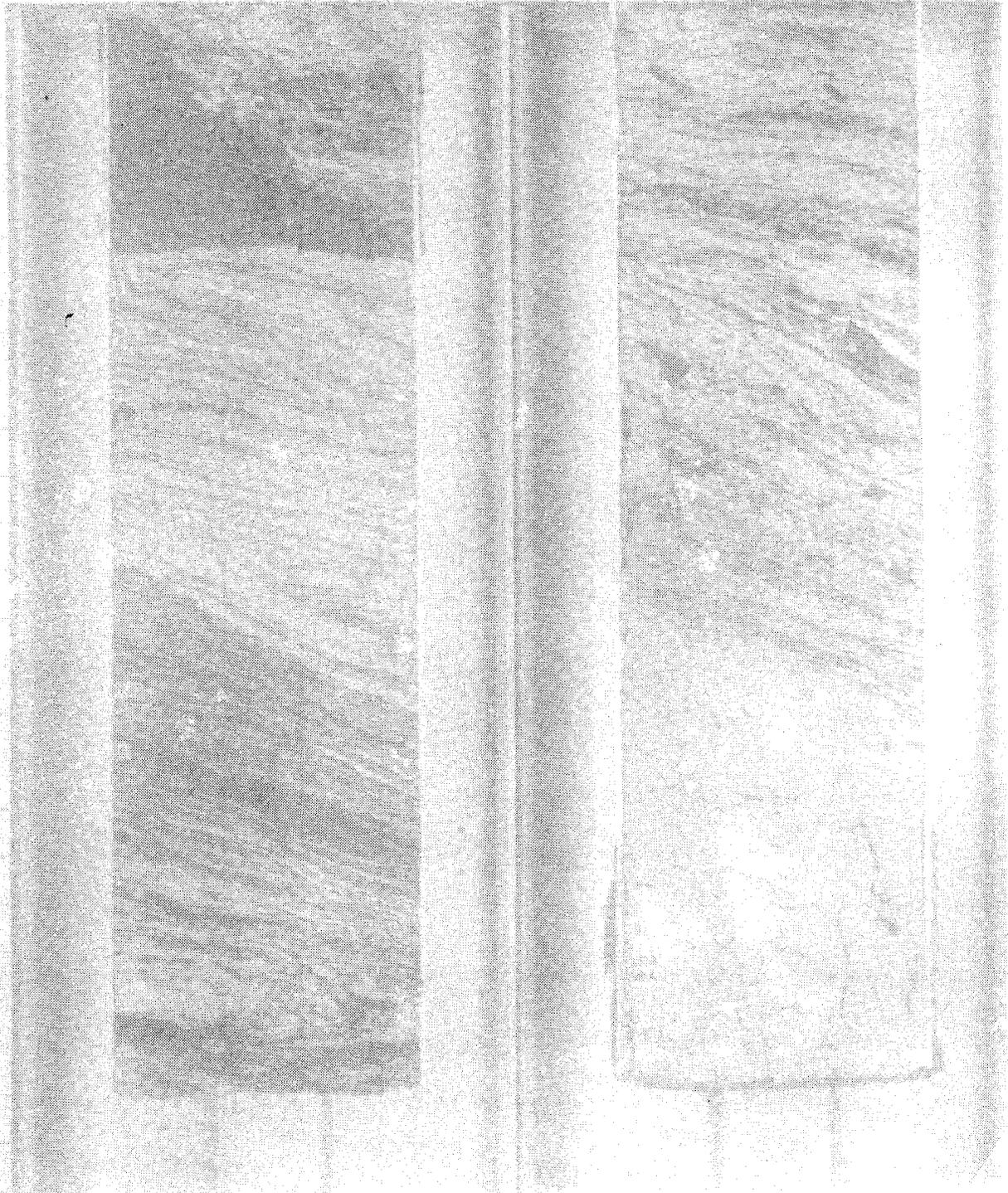


Fig. 2. SANDWICH flow chart of program steps.



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Fig. 3. Core photograph from laminated interval in oil field reservoir.

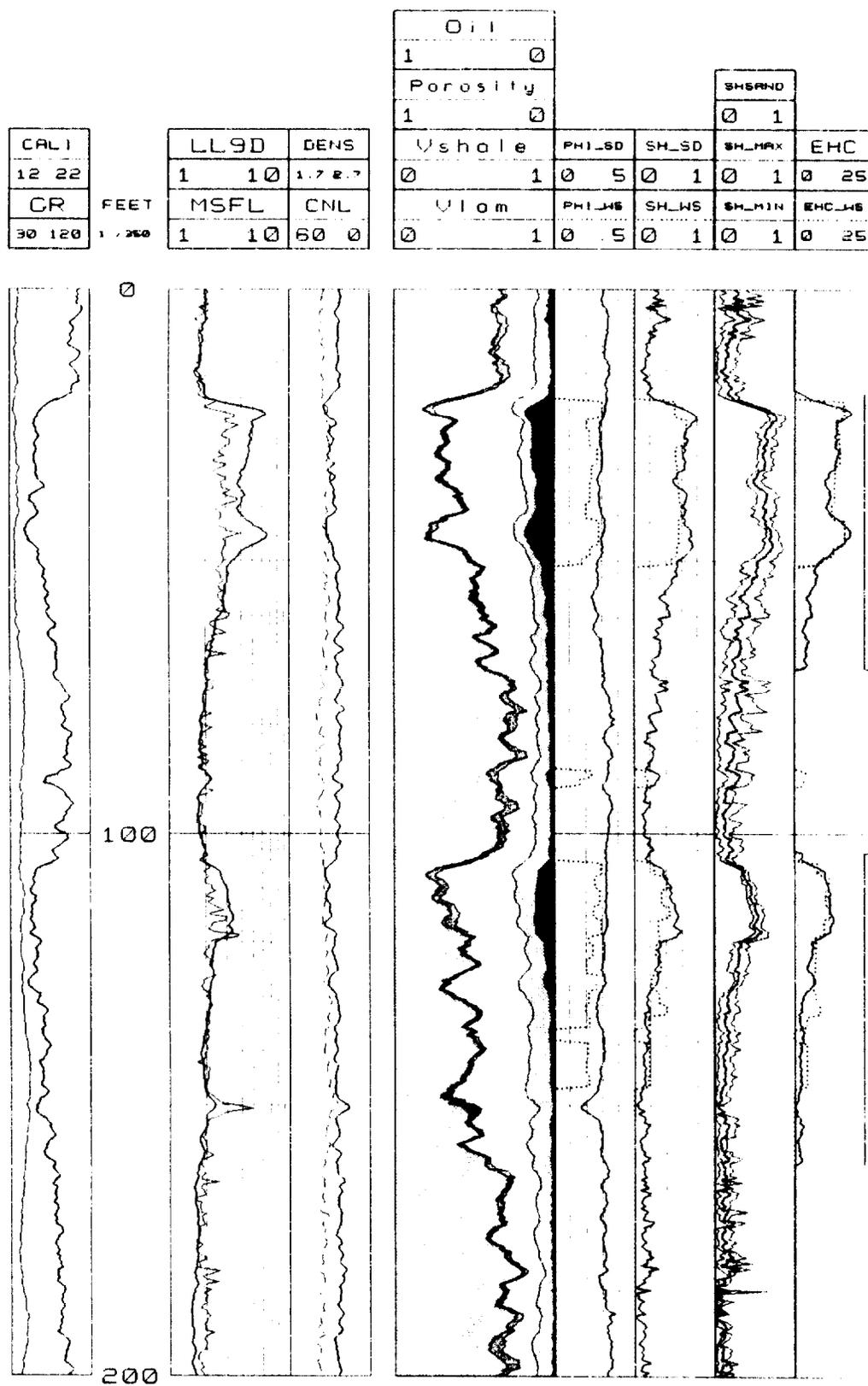
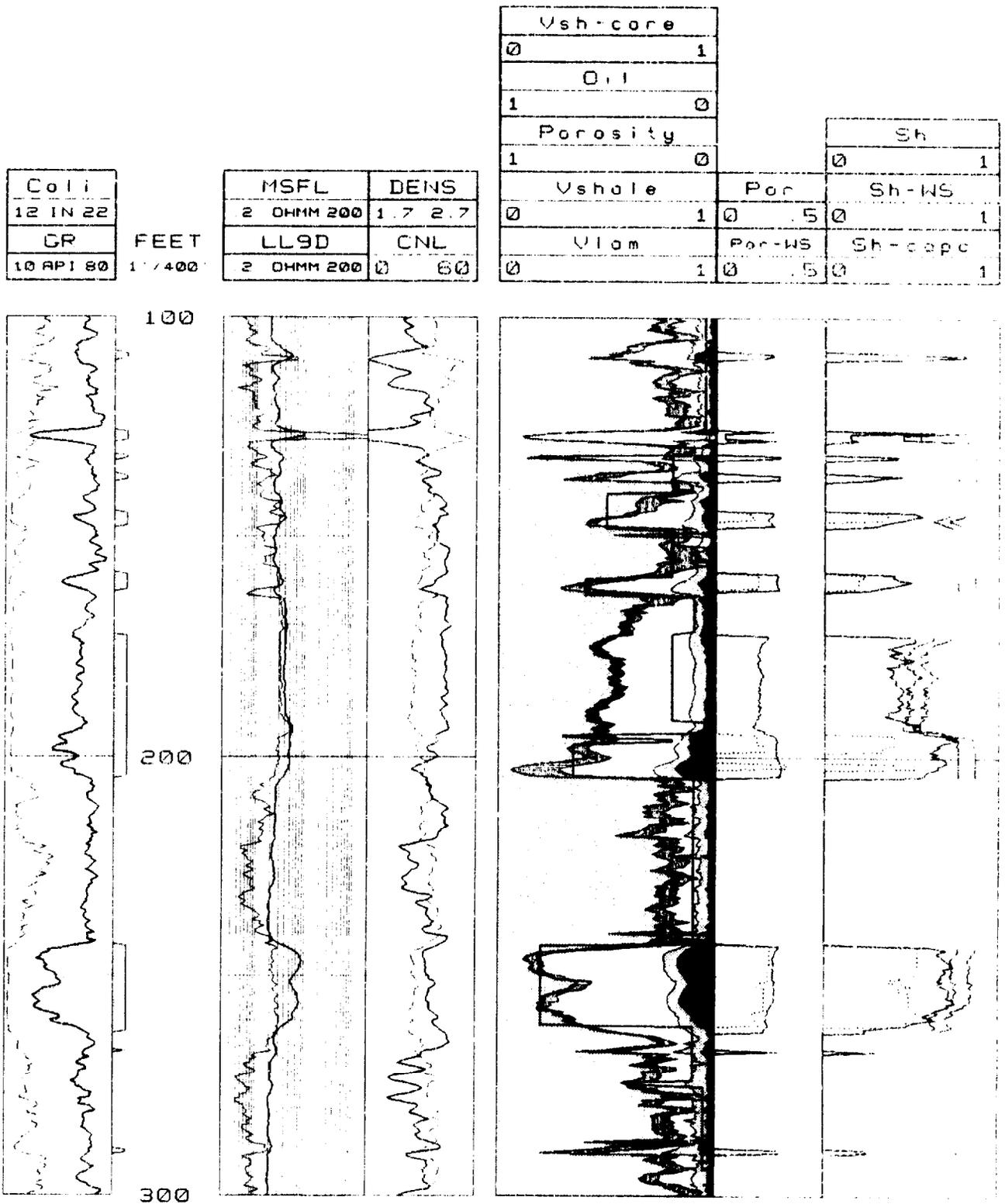


Fig. 4. Example output from SANDWICH evaluation.



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Fig. 5. Comparison of SANDWICH log evaluation with core shale fractions and cap curve data.

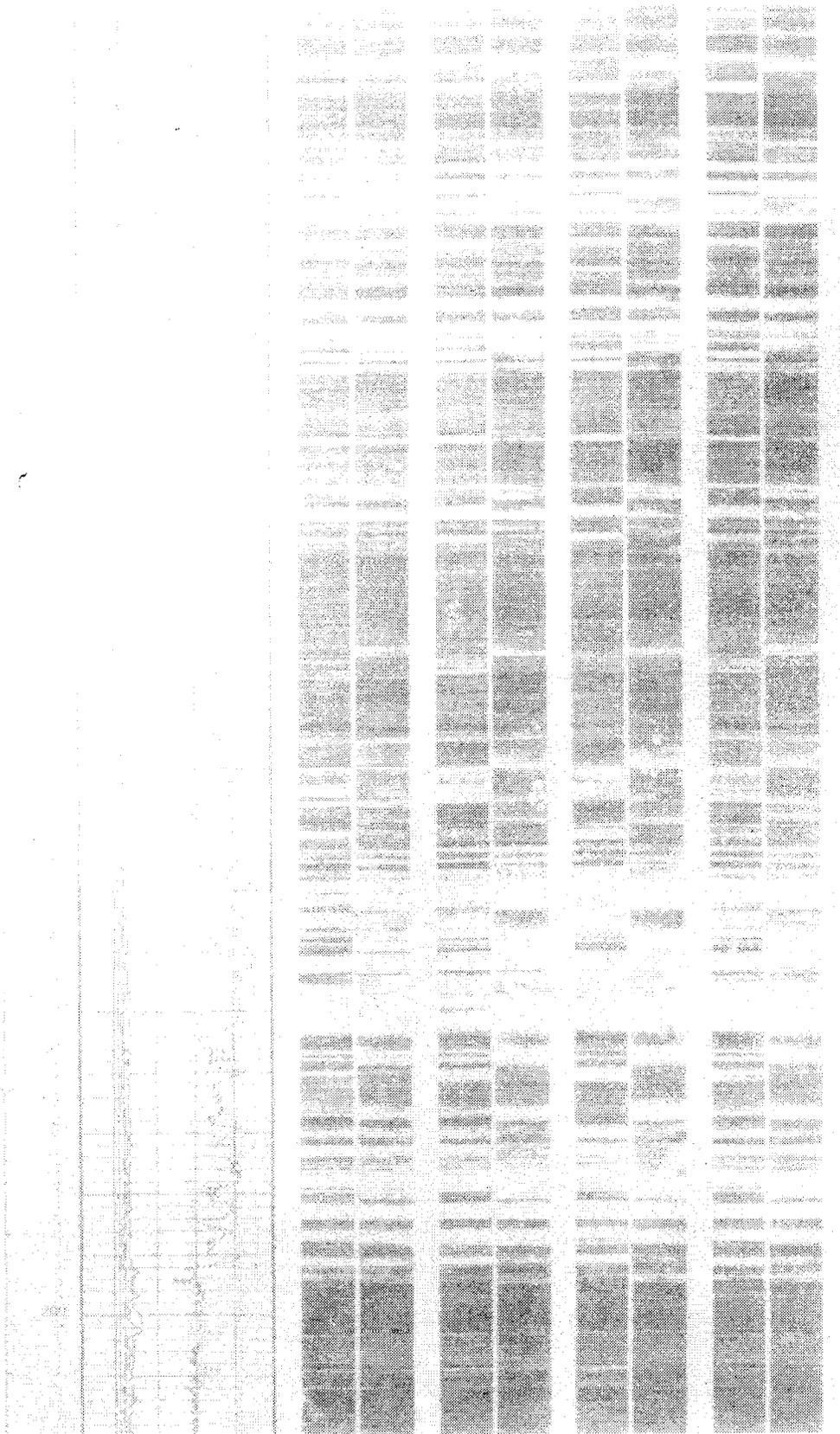
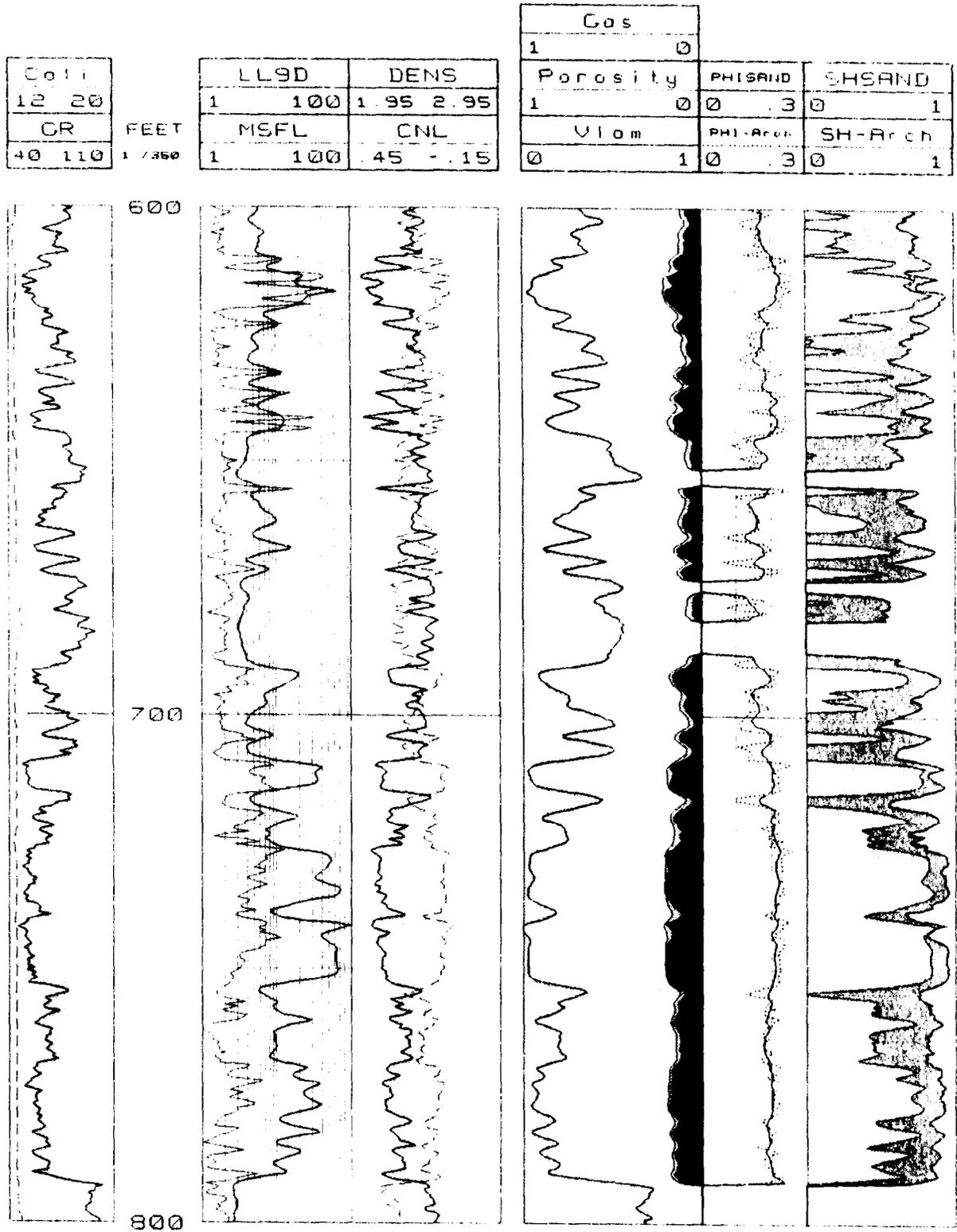


Fig. 6. Borehole image log in highly laminated gas-bearing formation.



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Fig. 7. Example of SANDWICH result in the highly laminated formation of Fig. 6.

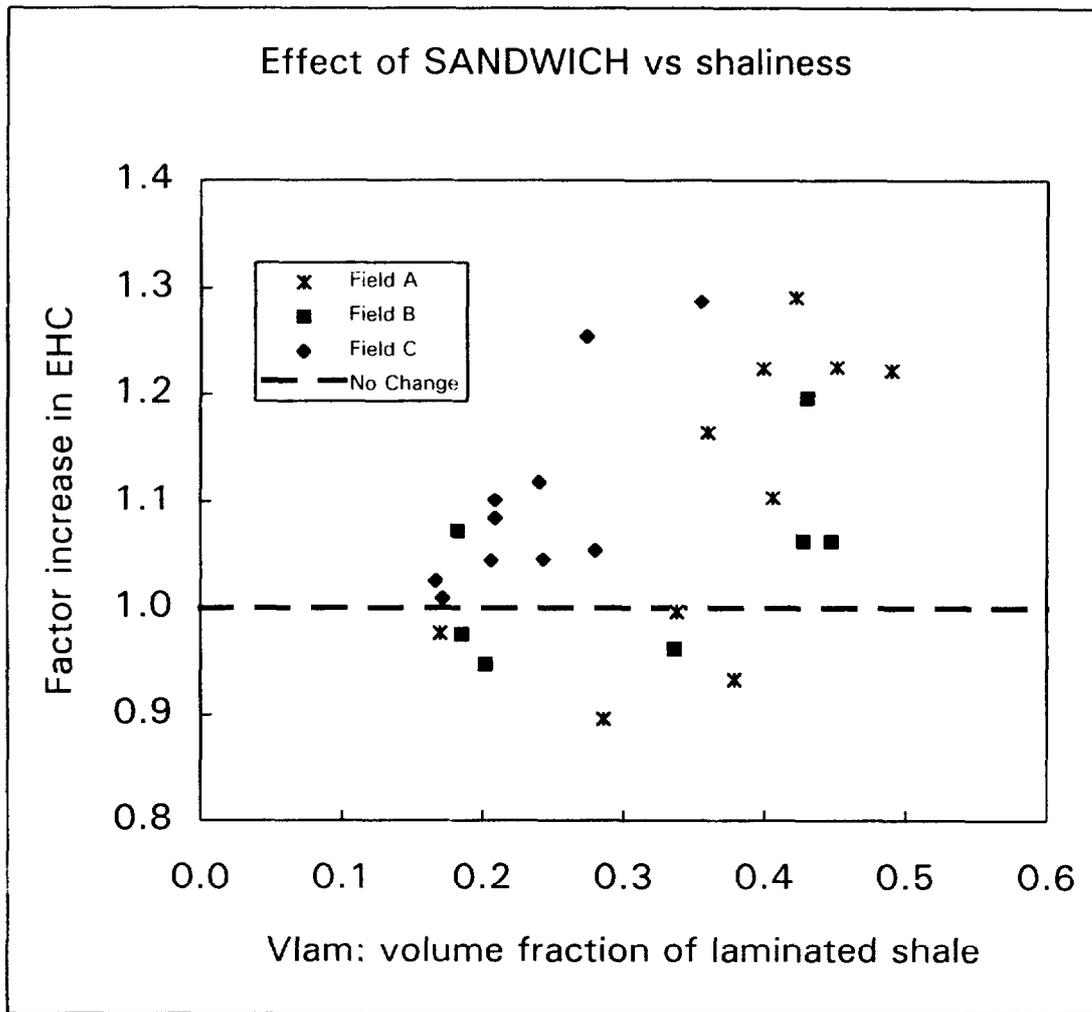


Fig. 8. Increase in equivalent hydrocarbon column (EHC) from application of SANDWICH vs amount of laminated shale.