The use of porosity logs in lithology determination, lithostratigraphy and basin analyses

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In the oil industry logging service companies have developed refined tools for measuring porosity and methods for determining the complex lithology of drilled rock sequences. The method of using porosity logs, the neutron porosity and bulk density logs, in combination with gamma ray and interval transit time (sonic) logs in lithological interpretation is demonstrated. Properly calibrated and scaled, the logs can be used to distinguish the lithology of single beds and rock successions. These can be correlated from well to well within a basin. Log responses comparable to rock successions found in the Norwegian-Danish Basin are used and illustrate the use of logs to erect lithostratigraphical units and for basin analyses.

Over the years there has been a need to supplement the information gained through cutting and core analyses with petrophysical borehole measurements in order to distinguish the lithology and stratigraphy of the rock sequences drilled. The petrophysical properties of the rocks are measured by logging tools; by comparing the different responses of the tools, the lithology can often be determined with good accuracy.

From the older wells in the Danish area the petrophysical measurements are restricted to self potential, resistivity, and gamma ray recordings. In newer wells the above mentioned logs are supplemented with the borehole compensated sonic log and the compensated neutron formation density log (log and tool names according to Schlumberger Ltd.). These were originally constructed for measuring porosity, achieved by making the logging tools sensitive to lithology, and as such they have become a powerful tool in geological interpretation.

Methods

The tool most commonly run in deep wells by oil industry service companies is the borehole compensated sonic log with gamma ray and interval transit

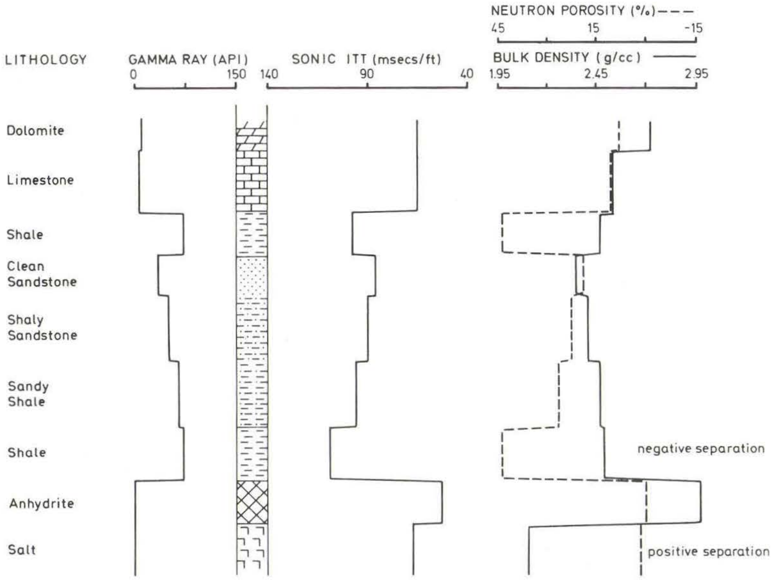


Fig. 1. Diagrammatic example of the response of borehole compensated sonic log and compensated neutron formation density log.

time logs. The gamma ray log records the natural radioactivity of the formation. In sedimentary rocks high gamma ray readings are generally caused by clay or potash rich minerals, e.g. glauconite and mica, whereas low readings may reflect sandstone, salt or carbonate. In clastic sequences the gamma ray response is most often caused by radiation from clay minerals. As the clay content in most cases decrease with increasing grain size the log can be used as clay and grain size indicator. The gamma ray response (in API units) in sandstone is in the range 15–50, in shales 60–120.

The interval transit time log is dependent on lithology, lithification, primary porosity, and the composition of fluid in the pores. The recording is in interval transit time units (msec/ft) which causes the values measured in a given lithology to decrease with increasing consolidation. In a formation with fixed porosity, shaliness will increase the interval transit time. In clean sandstone of 20% porosity the sonic log will give a reading of about 80 (msec/ft), in limestone and dolomite about 75 (msec/ft).

The simultaneous compensated neutron formation density tool is a combination of three logs, a compensated neutron porosity (%), a bulk density (g/cc) and a gamma ray log. The latter is used for correlation with the sonic tool. As a general rule, the compensated neutron porosity log responds to the hydrogen content of the formation. In water filled rock sequences the log

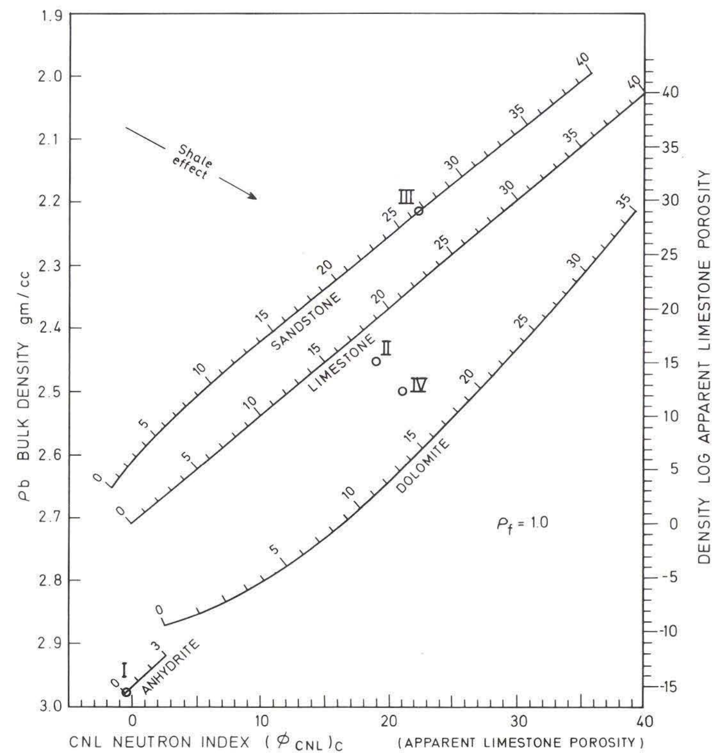


Fig. 2. Crossplot of bulk density and compensated neutron porosity log for determination of lithology and porosity. Roman numerals are crossplots of values from fig. 3a – 3d. (From Schlumberger Interpretation Charts 1972).

readings will primarily reflect the amount of liquid filled porosity. When gas is present, the lower concentration of hydrogen will produce a lower and spurious porosity value, in rocks with hydrated minerals such as gypsum and polyhalite or clays with bound water the readings are higher than the effective porosity. However, these departures are diagnostic and useful in lithology determination. The density log responds to the electron density of the formation which is related to the true bulk density of the rock. In porous liquid filled sedimentary formations the log is calibrated to read directly the bulk density, which is dependent on the rock matrix, porosity and fluid in the pores.

In order to use the compensated neutron porosity and the bulk density logs as lithology indicators, they have to be recorded on compatible scales. This is achieved by calibrating the neutron log to limestone porosity (Lpu) with a

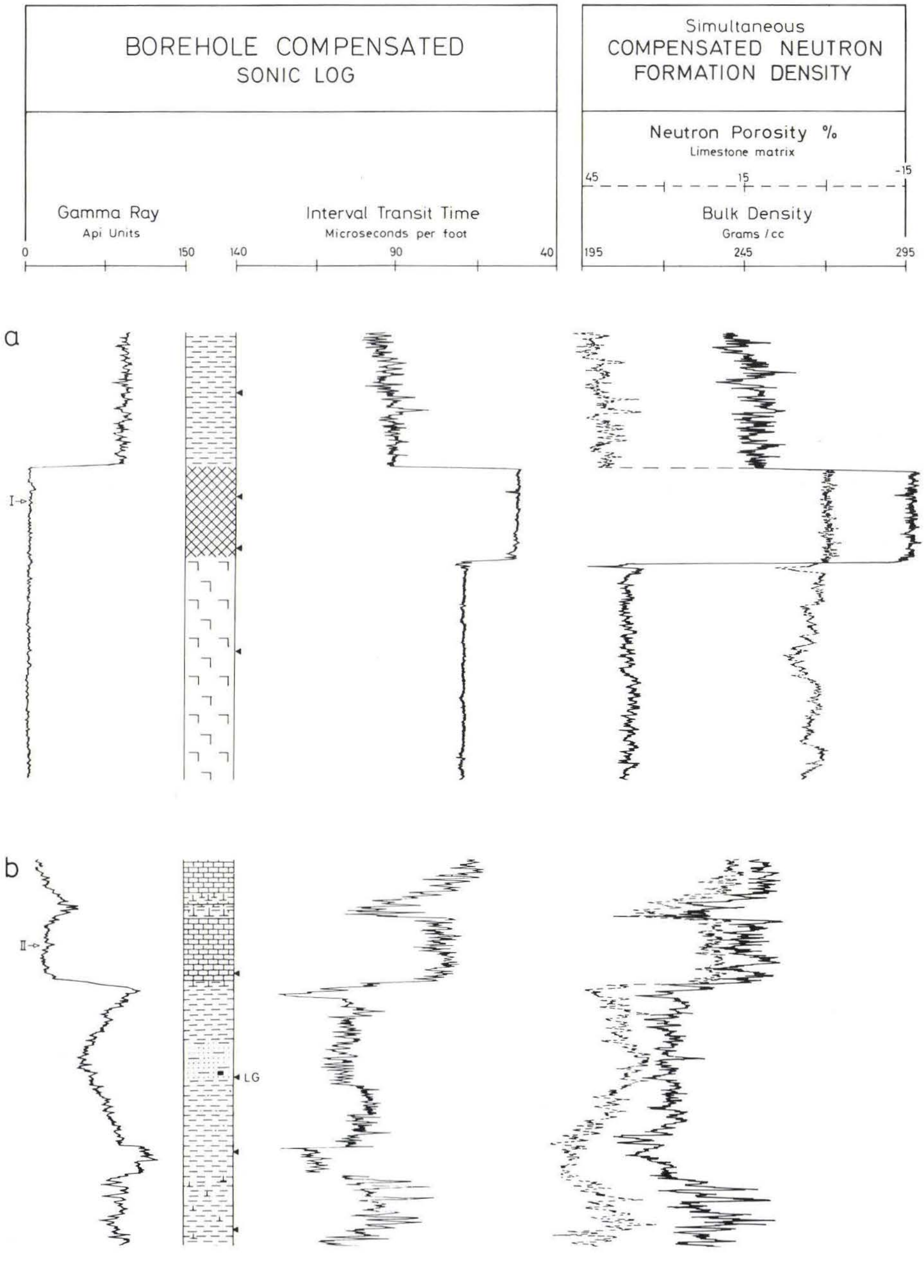
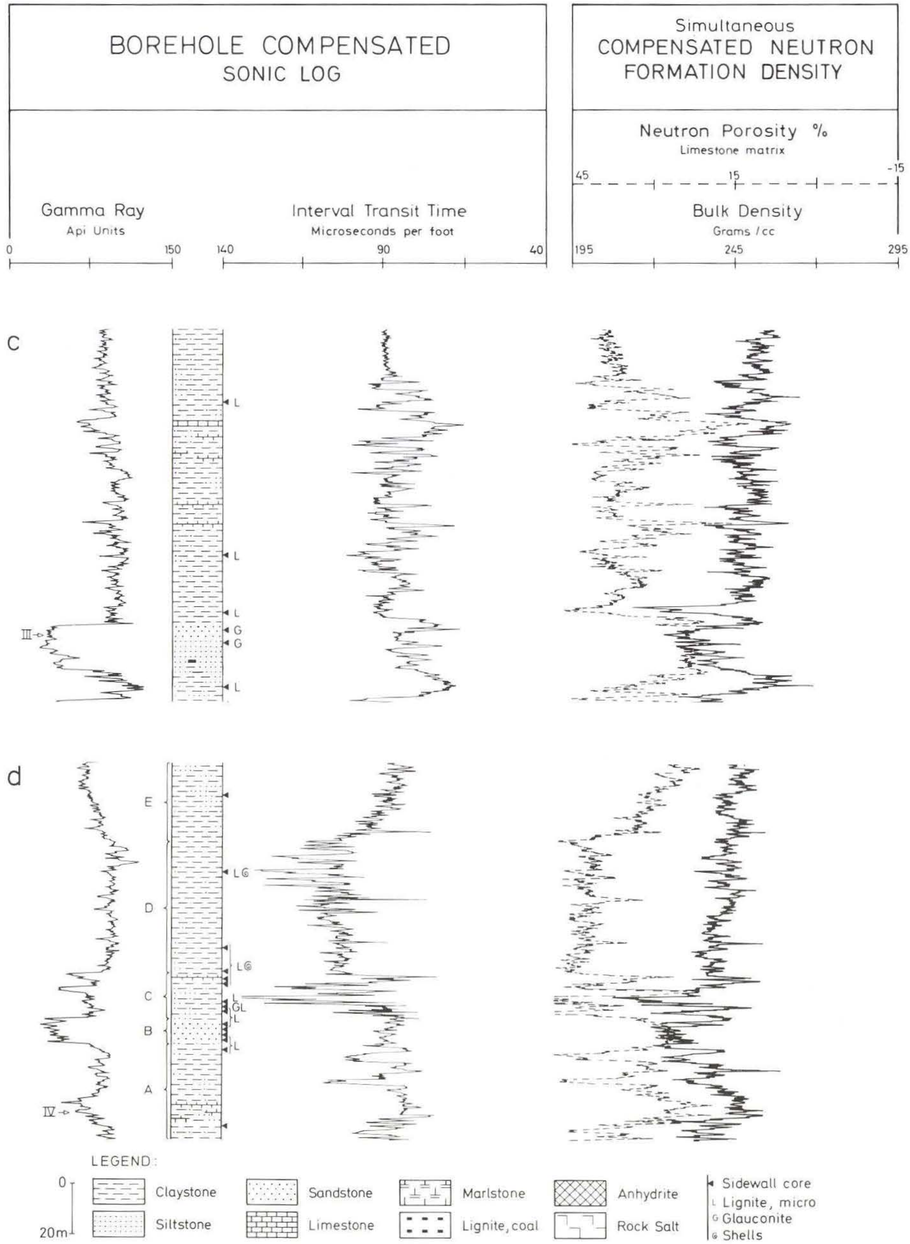


Fig. 3a–3d. Log pattern and lithological interpretation from borehole compensated sonic log and simultaneous compensated neutron formation density log.


BOREHOLE COMPENSATED
SONIC LOG
Simultaneous
COMPENSATED NEUTRON
FORMATION DENSITY
Neutron Porosity %
Limestone matrix
45
15
-15
Gamma Ray
Api Units
0
150
Interval Transit Time
Microseconds per foot
140
90
40
Bulk Density
Grams / cc
195
245
295
c
d
E
D
C
B
A
LEGEND:
0
20m
Claystone
Siltstone
Sandstone
Limestone
Marlstone
Lignite, coal
Anhydrite
Rock Salt
Sidewall core
Lignite, micro
Glauconite
Shells

sensitivity of 30 Lpu/track and recording the density log with a sensitivity of 0,5 g/cc/track (Schlumberger 1974). The overlay of the two logs with the neutron zero porosity point coinciding with a bulk density of 2.70 g/cc permits visual qualitative interpretation of the lithology (see fig. 1). As 2.70 g/cc for practical purposes is equal to the matrix density of limestone the log-curves in a pure limestone will superimpose regardless of porosity, while the separation and the measured values in other lithologies will be diagnostic. Fig. 1 gives a schematic example of qualitative interpretation from gamma ray, interval transit time, neutron and density logs of common lithologies.

In shales the neutron porosity will read between 15 and 50% with a negative separation from the bulk density of 10–45%. A clean sandstone will have a positive separation of 6–8% and the neutron porosity will range from zero to 30% – more in unconsolidated sand. Due to their higher density, shaly and micaceous sandstones have a negative separation. This is also characteristic of dolomite and anhydrite, while a marked positive separation is diagnostic of salt. Quantitative lithological interpretations can be made by crossplotting different log readings. Here as well as in qualitative interpretations clay correction, proper calibration and adjustment of logs to borehole conditions play an essential role before proper interpretations can be made. Most suitable for lithological analyses in clastic sequences are crossplots of bulk density and compensated neutron log values, fig. 2. Points corresponding to particular water saturated, pure lithologies define quartz-, limestone-, and dolomite-lines, which are graduated in porosity units. In mixed lithologies the points plotted from the log readings will fall between the corresponding lithology lines. Shaliness causes the points to lie to the right of the proper lithology line. Points marked with roman numerals correspond to crossplots of values from fig. 3a – 3d. I and III exemplify clean anhydrite and sandstone, II a dolomitic limestone and IV a shaly limestone.

Lithological interpretations

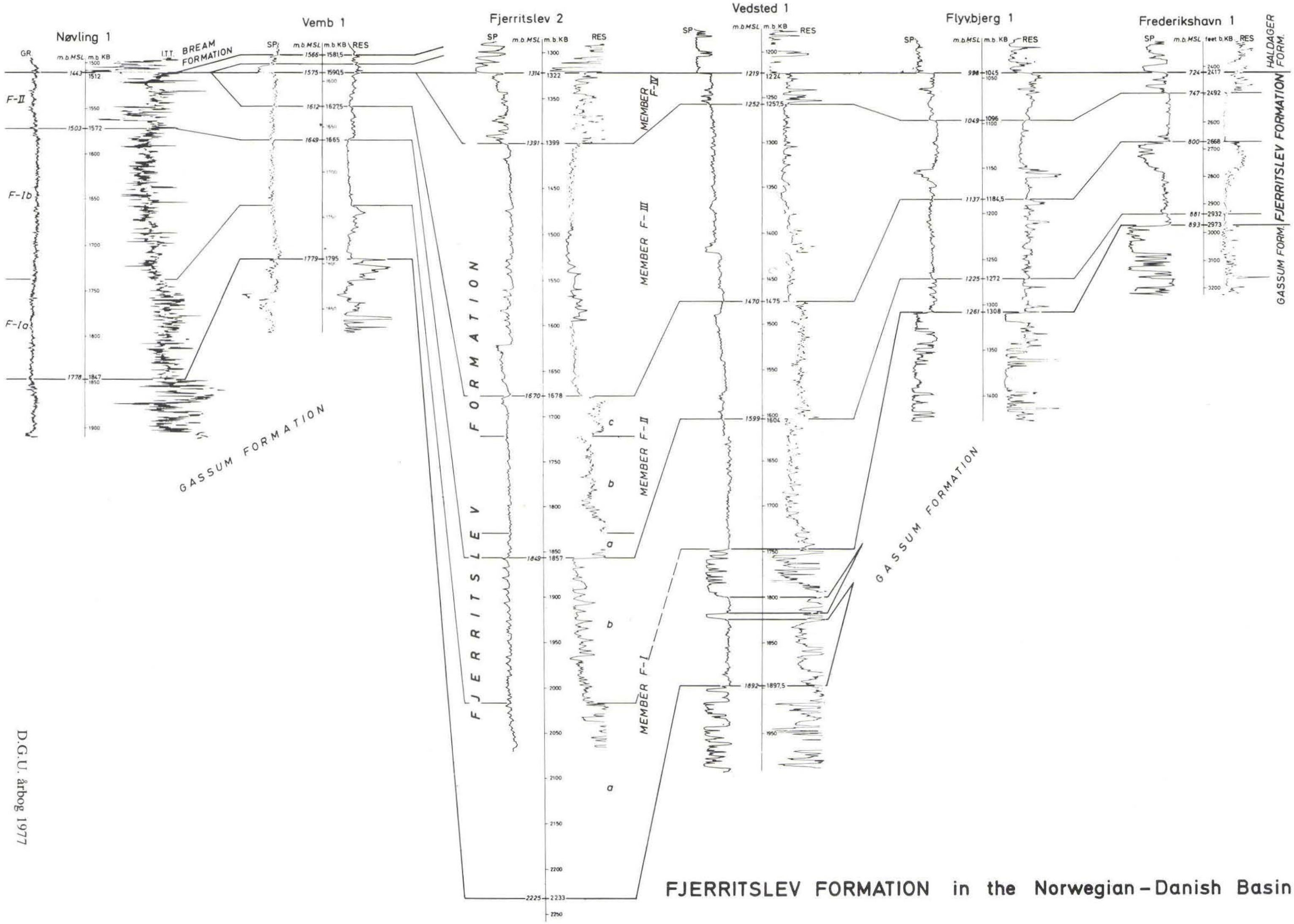
Figs. 3a – 3d show examples of lithological interpretations based on the above mentioned logs, sidewall cores and a general knowledge of the logged sequences.

Fig. 3a presents a succession of rock salt, anhydrite and claystone. The salt is characterized by low sonic log readings and a positive separation between the neutron and bulk density curves. The separation becomes negative in the above lying anhydrite because of the high bulk density values. In the salt dome province of the Norwegian-Danish Basin the sequence could represent a salt dome with a cap rock such as found in the Uglev 1 well (Sorgenfrei & Buch 1964).

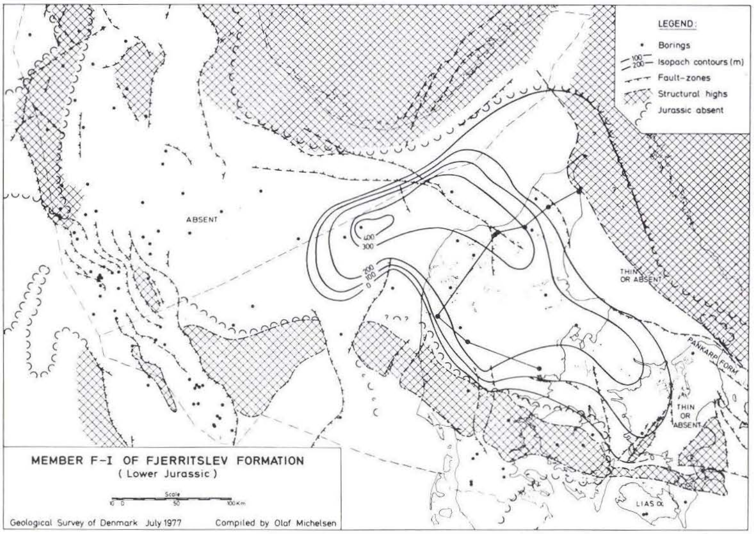
The lowest of the sequence in fig. 3b is interpreted as a claystone. The irregular curve pattern with several marked peaks shows that small marlstone streaks occur in the claystone. Upwards the claystone becomes silty and a poorly sorted layer of siltstone is present. A sidewall core shows that the siltstone is micaceous, glauconitic and contains coal-fragments. This points to a marine basin marginal deposition. From the claystone there is an abrupt change over a marlstone bed to limestone, which contains some clay or might be slightly dolomitic as the neutron and bulk density curves have a small negative separation. In the middle of the limestone the curves indicate the presence of a marlstone layer. The described log pattern is characteristic of the lithological changes from the Lower to the Upper Cretaceous in the central part of the Norwegian-Danish Basin as found in the Fjerritslev 2 and Haldager 1 wells (Sorgenfrei & Buch 1964). The poorly sorted silt-, sand-, and marlstones are characteristic of the Lower Cretaceous shallow water deposits. The Upper Cretaceous is dominated by calcareous deposition with almost no terrigenous sediment influx.

The curve pattern in the lower part of the section, fig. 3c, is very characteristic of sandstones, showing low gamma ray values, and a marked change in the compensated neutron formation density log to a small positive separation. The curve pattern and the sidewall cores indicate an upwardly coarsening sandstone. In the lower part it contains coal-fragments, whereas the upper part contains glauconite and is calcite cemented. The depositional environment can be interpreted as deltaic. The lower coalbearing sandstone may be a distributary mouth bar deposit (Goetz et al. 1977), and the top part may represent a marine shoal sand (Selley 1976). Claystone and shale with characteristic high gamma ray and interval transit time values superpose the sandstone. The occurrence of clastic influx and thin limestones in the sequence point to deposition in a shelf environment. The described log pattern is characteristic of the transition from the Gassum Formation (Upper Triassic) to the Fjerritslev Formation, Member F–I (Lower Jurassic), cf. fig. 4.

The lower part of fig. 3d (section A) might also represent a shelf deposit as judged from the occurrence of silt- and limestone layers, but sidewall cores contain an impoverished fauna of microfossils, many of which are only preserved as pyrite-casts pointing to sedimentation in a reducing environment. The gamma ray and compensated neutron formation density logs indicate that the overlying sequence is a marked sandstone (section B). The wide basin occurrence and petrography determine the sandstone as deltaic-fluvial sheetsand deposits, comparable with the Haldager Sand (fig. 5). The sandstone is overlain by marine clay- and sandstones, shale, and uppermost silt- and claystone (section C). The marine clay- and sandstones have very nervous curve patterns. The gamma ray log reveals an upwardly coarsening and



FJERRITSLEV FORMATION in the Norwegian-Danish Basin



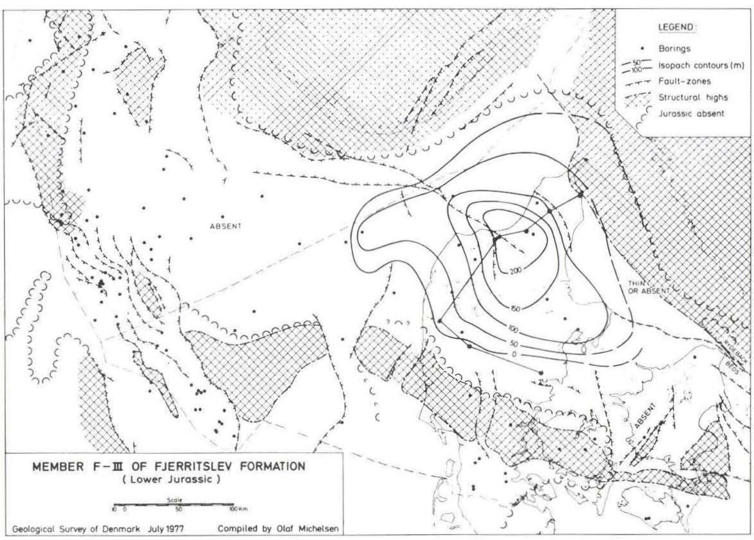


Fig. 4b. Isopach maps of members F–I and F–III exemplifies the basin development of the Lower Jurassic (modified from Michelsen 1978).

Fig. 4a. Cross section, as shown on fig. 4b, of the Fjerritslev Formation through the Norwegian-Danish Basin (modified from Michelsen 1978).

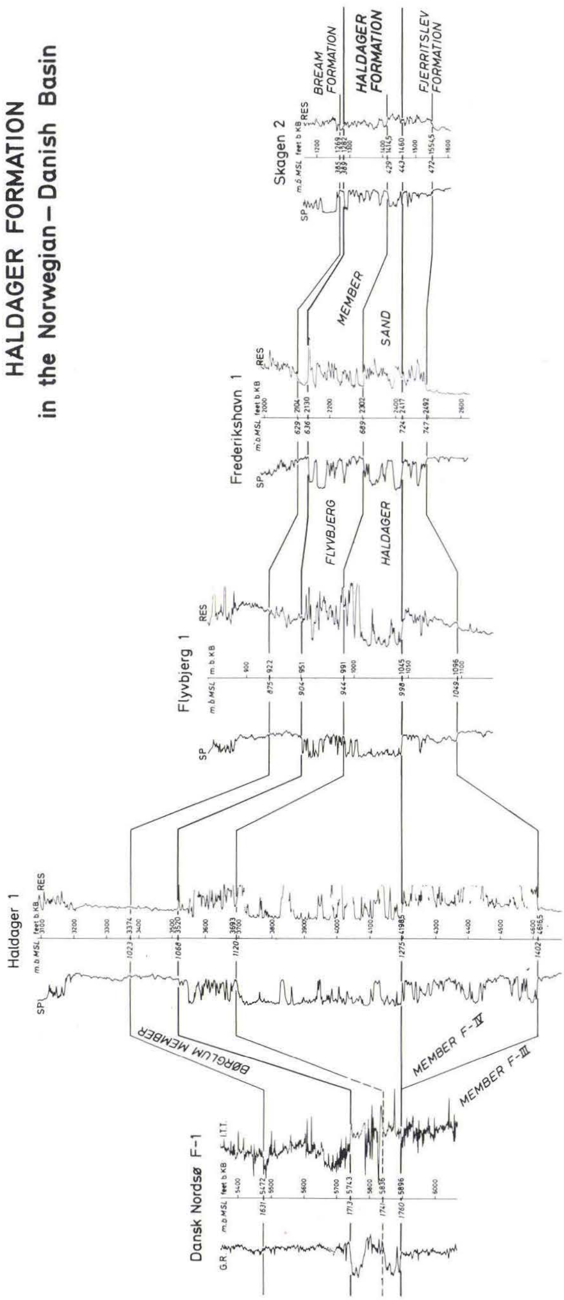


Fig. 5a. Cross section, as shown on fig. 5b, of the Haldager Formation (modified from Michelsen 1978).

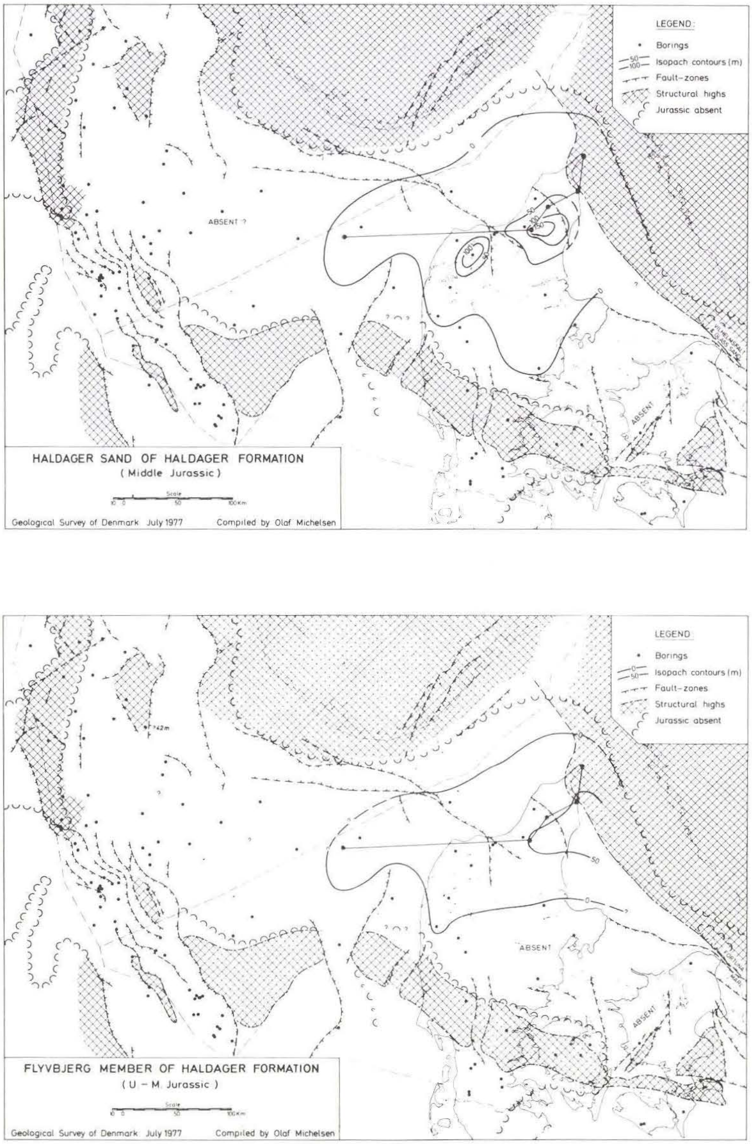


Fig. 5b. Isopach maps of the Haldager Sand and Flyvbjerg Member (modified from Michelsen 1978).

regressive pattern, which might be due to subsidence and drowning of the deltaic-fluvial deposits followed by successive clastic fill. The sequence is terminated by a calcite cemented sandstone. The overlying marine shale (section D) with gamma ray, interval transit time, neutron and bulk density readings represents a subsidence of the basin. An increasing silt content in the uppermost part (section E) is registered by a decrease in the measured values. The increasing silt content is due to new regressive tendencies in the basin. The succession of log patterns in fig. 3d is characteristic of the transition from the marine Fjerritslev Formation, Lower Jurassic, over the deltaic and shallow marine Haldager Formation, Middle Jurassic-Oxfordian to the marine Bream Formation, Upper Jurassic (cf. Michelsen 1978).

The above mentioned examples demonstrate the possibilities for making lithological and environmental interpretations of the drilled sequences and for defining boundaries between lithostratigraphical units with the aid of wire line logs. On the basis of newer wells, where a delicate lithostratigraphy can be erected because compensated neutron formation density logs are run, it is possible to reinterpret the older wells in the Danish area where petrophysical measurements are restricted to self potential, resistivity and gamma ray logs. This is exemplified by fig. 4 and 5 which show the lithostratigraphical subdivision and basin development of the Lower Jurassic Fjerritslev Formation and the Middle Jurassic Haldager Formation in the Norwegian-Danish Basin.

Dansk sammendrag

Ved den geologiske analyse af dybdeboringer er det nødvendigt at supplere cuttings og kærne analyser med petrofysiske målinger for at klarlægge de gennemborede lags lithologi og stratigafi.

For ældre boringer er der af olieselskaberne foretaget SP, resistivity og gamma ray målinger. I nye boringer er der desuden foretaget massefylde og porøsitets målinger med borehole compensated sonic og compensated neutron formation density logs. Disse er indenfor olieindustrien udviklet med henblik på porøsitetsmålinger af de gennemborede lagserier, men korrigeret og kalibreret som vist på fig. 1 er det muligt at benytte de petrofysiske målinger til en kvalitativ lithologisk bestemmelse (fig. 3a–d). Kvalitative analyser af målingerne foretages ved crossplots (fig. 2). Efter vurdering af lithologien og korrelation til andre boringer kan der opstilles tværprofiler, der viser de stratigrafiske enheder og bassin udviklingen (fig. 4 & 5).

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