# Pressure indicators from the sedimentary basins of West Greenland

Kevin J. Bate

Open File Series 95/13

December 1995

GRØNLANDS GEOLOGISKE UNDERSØGELSE
Ujarassiortut Kalaallit Nunaanni Misissuisoqarfiat
GEOLOGICAL SURVEY OF GREENLAND

GRØNLANDS GEOLOGISKE UNDERSØGELSE
Ujarassiortut Kalaallit Nunaanni Misissuisoqarfiat
GEOLOGICAL SURVEY OF GREENLAND
Øster Voldgade 10, DK-1350 Copenhagen K, Denmark

The Geological Survey of Greenland (GGU) is a research institute affiliated to the Mineral Resources Administration for Greenland (MRA) within the Danish Ministry of Environment and Energy. As with all other activities involving mineral resources in Greenland, GGU's investigations are carried out within the framework of the policies decided jointly by the Greenland Home Rule Authority and the Danish State.

**Open File Series**

The Open File Series consists of unedited reports and maps that are made available quickly in limited numbers to the public. They are a non-permanent form of publication that may be cited as sources of information. Certain reports may be replaced later by edited versions.

**Citation form**

*Open File Series Grønlands Geologiske Undersøgelse*

conveniently abbreviated to:

*Open File Ser. Grønlands geol. Unders.*

GGU's Open File Series består af uredigerede rapporter og kort, som publiceres hurtigt og i et begrænset antal. Disse publikationer er midlertidige og kan anvendes som kildemateriale. Visse af rapporterne vil evt. senere blive erstattet af redigerede udgaver.

ISSN 0903-7322

GRØNLANDS GEOLOGISKE UNDERSØGELSE

Open File Series 95/13

# Pressure indicators from the sedimentary basins of West Greenland

Kevin J. Bate

December 1995

Abstract

Drilling results of the five offshore wells suggest that the offshore southern West Greenland Basin is an area of generally normal pressure, with only limited evidence for overpressured units. The predominance of sandy or coarse clastic lithologies within the Upper Tertiary succession precludes the generation of overpressure and allows the basin as a whole to attain equalised pore pressure. However, in two of the wells, Kangâmiut-1 and Ikermiut-1, mudstones of Paleocene and Eocene age have pore pressures above hydrostatic pressure. The onset of abnormal pressures in these wells corresponds to an increase in the source potential of the mudstones. It can be concluded that the Paleocene and Cretaceous successions in the basin are likely to be overpressured where they conform to the top of the oil generative window.

*K. J. B., Geological Survey of Greenland, Øster Voldgade 10, DK–1350 Copenhagen K, Denmark*

## CONTENTS

Introduction . . . . . . . . . . 4
Definition of overpressure . . . . . . . . . . 4
Generation of overpressure . . . . . . . . . . 5
  Compaction disequilibrium . . . . . . . . . . 5
  Aquathermal pressuring . . . . . . . . . . 6
  Montmorillonite dehydration . . . . . . . . . . 6
  Depositional environment . . . . . . . . . . 7
  Generation of hydrocarbons . . . . . . . . . . 7
  Tectonics . . . . . . . . . . 7
Well planning . . . . . . . . . . 8
Overpressure indicators . . . . . . . . . . 8
  Engineering indicators . . . . . . . . . . 9
  Mud properties . . . . . . . . . . 10
  Geological indicators . . . . . . . . . . 10
  Petrophysical indicators . . . . . . . . . . 11
Indications of overpressure offshore southern West Greenland . . . . . . . . . . 12
  Nukik–1 . . . . . . . . . . 13
  Nukik–2 . . . . . . . . . . 14
  Hellefisk–1 . . . . . . . . . . 16
  Ikermiut–1 . . . . . . . . . . 17
  Kangâmiut–1 . . . . . . . . . . 19
Indications of abnormal pressure onshore West Greenland . . . . . . . . . . 23
Prediction of overpressure in southern West Greenland . . . . . . . . . . 24
Summary and conclusions . . . . . . . . . . 26
Acknowledgements . . . . . . . . . . 27
References . . . . . . . . . . 28
Figures
Appendix 1
Appendix 2

**Introduction**

This report compiles and summarises the evidence for abnormally pressured rock units in the sedimentary basins of West Greenland as provided by the drilling results of five offshore exploration wells and four shallow onshore boreholes (Fig. 1). The area covered by the report stretches from 62° N to 71° N and includes both onshore and offshore areas. Prior to the presentation of the data from West Greenland, the causes of overpressure and the various techniques employed to record overpressure during drilling are summarised.

During the period 1970 to 1979 the continental shelf was explored for hydrocarbons by many major oil companies. To this end over 40 000 km of reflection seismic data were acquired with the exploration effort culminating in the drilling of five offshore exploration wells in 1976–1977. All five wells were declared dry, and all concessions were relinquished by 1979. However, data from this phase of exploration have contributed to the understanding of the regional geology of the area (Chalmers & Pulvertaft, 1993; Chalmers *et al.*, 1993).

The sedimentary basins of West Greenland were formed in response to the rifting of West Greenland from North America in the Mesozoic and the opening of the Labrador Sea in the Early Tertiary. More than five kilometres of Mesozoic and Cenozoic sediment has accumulated in these depocentres.

In this report the pressure regime in the basins will be summarised and an attempt made to highlight areas that may be overpressured to aid the well planning at future drill sites.

**Definition of overpressure**

Formation pressure is the pressure acting on fluids (formation water, oil, gas) in the pore spaces of the formation. Normal formation pressures will equal the hydrostatic pressure, i.e. the weight of interstitial fluids (height of fluid column × unit weight of fluid) extending from the surface to the subsurface formation (Fertl & Chilingarian, 1977).

The pressure/depth gradient of a free-standing column of fresh water extending from the surface to the subsurface formation is 0.10 kg $cm^{-2}m^{-1}$ (0.433 psi/ft) and for a saturated salt solution, 0.1074 kg cm $^{-2}m^{-1}$ (0.465 psi/ft). Abnormal formation pressures are therefore characterised by any departure from the normal trend (Fig. 2). Pascal stated that if an external pressure is applied to a confined fluid at rest, the pressure at every point within the fluid is increased by the amount of the external pressure. Pore fluids within sealed units are examples of fluids confined within a sealed compartment.

Overpressure develops when the pore pressure of formation fluids is prevented from attaining a normal hydrostatic pressure. If a rock unit becomes sealed off from the surrounding sediments, it will not have hydraulic pressure communication with other units or with the overlying hydrodynamic regime (Hunt, 1990). This implies that rock units with abnormal pressure must become sealed within an impermeable lithology, the result being that the fluids in the sealed porous unit have a different and possibly higher pore pressure than that of the surrounding mudstone.

**Generation of overpressure**

The causes of overpressure are numerous and can be related to diagenesis, depositional environment, tectonism, and also to the generation and migration of hydrocarbons. Considering the influence that abnormal pressures have upon drilling and safety, relatively little work has been carried out on the subject.

Compaction disequilibrium

As sediment is progressively buried, a gradual compaction takes place. If sedimentation is slow the sediment will adjust to the additional load imposed by the overlying sediments. As mineral grains are pressed together pore water is expelled, and pore pressures will remain in equilibrium if there is adequate fluid communication between pores and other layers.

For this equilibrium to be maintained a delicate balance must exist between sedimentation rate, permeability, reduction of pore space and ability of excess pore fluids to be removed. If one or more of these processes become restricted the expulsion of water is impeded. This is known as compaction disequilibrium (Magara, 1975). For example, should the rate of sedimentation increase to a level such that the amount of clay deposited in unit time exceeds the amount that produces equilibrium conditions, the process of dewatering will be restricted. Thus the magnitude of sedimentation increase over equilibrium conditions produces a proportionate increase in pore pressure. Because the excess pore fluids cannot escape they help support the overburden, therefore retarding further compaction and reducing the bulk density of the lithology.

Aquathermal pressuring

Should a rock unit become isolated and taken to greater depth, rising temperature will induce higher than normal pore pressures. This process is called aquathermal pressuring (Barker, 1972). It is influenced by the geothermal gradient and is linked to the process of compaction disequilibrium.

Montmorillonite dehydration

The diagenetic alteration of clay minerals is an important process in the generation of overpressure. The alteration of montmorillonite to illite liberates interlayer-bound water which becomes free pore water (Burst, 1969). In this way water and space are added to the interparticle area. This process is termed montmorillonite dehydration (Powers, 1967). The phase change from bound to free water has an associated decrease in the density and increase in volume of the water. In this new state, water literally produces effective porosity and permeability with the water effectively supporting the overburden. The liberated water within the newly created pore spaces is prevented from escaping by sealing formation. The compressibility of water is low and the problem becomes analogous to that of trying to cram more water into a container that is already full.

A combination of abnormal pressure, abnormal shale porosity and sub-normal bulk density initially may be created by compaction disequilibrium. When rocks contain large quantities of water (porosity), the geothermal gradient becomes elevated due to the fact that the heat conductivity of water is less than that of the rock matrix. These conditions increase the chances for montmorillonite in the abnormal pressure zones to release its interlayer water and transform to illite. Montmorillonite dehydration and consequent water expansion can further increase the pore-water pressure.

## Depositional environment

Overpressure is frequently produced in sediments that have been rapidly deposited (Dickinson, 1953). The rapid burial of clastic units within argillaceous sediments prevents the dewatering and pressure equalisation of the fluids within the porous sand bodies. Such conditions are typical in deltaic environments. The mudstones prevent the fluids in the sand unit from communicating with surface and/or other sand bodies and attaining normal pore pressure. The situation is compounded as the sand unit is taken to greater depths by further burial.

## Generation of hydrocarbons

An important mechanism for the creation of overpressure is associated with the generation of hydrocarbons within source rocks (Hunt, 1990). During the drilling of a well it is often noted that there is a rise in pore pressure associated with a rise in the Total Organic Carbon (TOC) and Hydrogen Index of rocks. It is thought that the generation and primary migration of hydrocarbons within deeply buried mudstones occur below a sealing lithology, resulting in a pressure build-up within the bed. Pressures and temperature (Powers, 1967; Burst, 1969) can eventually reach such a level that the overlying seal is fractured and the hydrocarbons and other pore fluids then move vertically into overlying lower pressured units and accumulate in the nearest suitable trap.

## Tectonics

The processes of regional faulting, folding and diapirism can uplift formations and hence introduce abnormally high pressured formations to shallower areas of the crust (Gretener, 1977).

It has been noted that the granular structure of rocks above and below a thrust plane is relatively undeformed. A possible explanation could be that large volumes of pore fluids under high pressure can partially support the overburden thereby allowing large thicknesses of rock to "float" and move along the high pressure zone (Hubbert & Rubey, 1959). This tectonic loading can also introduce abnormally pressured units to lower levels of the crust.

**Well planning**

During the drilling of an exploration well the anticipated rise in pore pressure with increasing depth is controlled by the circulation of drilling mud down through the drill string and up the annulus (space between the drill string and the open hole and/or the casing). Mud weights are recorded as specific gravity (SG) or in pounds per gallon (ppg). Throughout this report a conversion factor of 0.11938 has been used to convert ppg mud weights to SG. Formation pressures are quoted in SG MWE (Mud Weight Equivalent).

The specific gravity or mud weight of the drilling fluid is controlled by the addition of chemicals, chiefly baryte, to slightly overbalance the expected pore pressures by about 0.02 to 0.047 SG. If the mud weight is too low, formation fluids will flow into the well bore and an under-balanced system will arise. Conversely, if the mud weight is too high, the formation may fracture leading to the destruction of potentially producible formations and loss of expensive drilling fluid into the formation. In an over-balanced system the rate of penetration (ROP) may also be slowed resulting in inefficient progress of the well.

At specific depths metal casing is lowered and cemented into the well to prevent the increasing mud weight from fracturing shallower formations. It is standard practice to perform a leak-off test immediately after the setting of casing and before the drilling of new hole. A leak-off test records the pressure at which the formation begins to fracture, thus providing information for the efficient planning of mud weights to be used during drilling of the next section of hole.

Overpressure becomes a drilling hazard when the drill bit intersects a formation with fluids under a pressure greater than the drilling mud can withhold. In this situation the formation fluids will flow into the annulus. This influx displaces the drilling fluid resulting in a gain of mud in the mud pits at surface. This is termed a kick. If the flowing well is not adequately controlled, the high pressure fluids may reach the surface, thereby jeopardising safety of personnel and equipment. This is termed a blow-out.

**Overpressure indicators**

Drilling parameters and logging-while-drilling (LWD) methods provide almost instantaneous information on subsurface pressures (Fertl & Chilingarian, 1977). Drilling mud and formation properties can also provide direct information concerning pressure, but this information is delayed by the time required to circulate the mud and cuttings to surface, i.e. the lag-time. Following drilling, petrophysical logging can provide "after the event" indications of overpressure.

A pressure gradient will exist between an overpressured unit and normally pressured units above and below. This potential gradient will cause a flow from the overpressured to the lower-pressured unit, with fluid pressures in the intervening zone varying between normal and the level of the overpressured zone. This is known as the pressure transition zone. Steadily rising amounts of connection and trip gas in conjunction with a decreasing bulk density trend may be indicative of a transition zone.

Engineering indicators

During drilling a number of engineering parameters are recorded by the wellsite pressure engineer to calculate a computer generated Dc-exponent. The Dc-exponent attempts to normalise rate of penetration for variations in mud weight, rotary speed (rpm), weight on bit (wob), bit type, bit wear, hole diameter and a normal formation pressure gradient, the aim of which is to indicate increasing formation pressure. A plot of Dc-exponent with depth should show a steady rise in value (Fig. 3). A reduction in the Dc-exponent and deviation of the trend line to the left indicates a rise in formation pressures. Another indication of overpressure is an increase in the torque value of the drill string. Overpressured formations often swell into the borehole thus decreasing the diameter of the hole and as a result imparting higher torque onto the drill string. Torque values are continually monitored during drilling at the wellsite by the contracted mudlogging company along with all other drilling parameters.

Associated with swelling formations is the stuck pipe situation. This occurs when the drill string is adjacent to an overpressured interval and the drilling fluid is under-balance, the result being that the formation pressure "sucks" the drill string onto the sidewall of the well. It is often the drill pipe above the bottom hole assembly (BHA) that becomes stuck due to the BHA having a far greater weight than the standard drill pipe. To free the pipe can be costly and very time consuming.

Mud properties

The most direct indications of overpressure are obtained once the drilling mud has been circulated back to surface. The returning mud can bring specific and direct evidence of the physical characteristics of the bottom hole environment.

As the hole deepens, more drilling mud is required to fill the hole, as recorded by a steady fall in the volume of mud in the mud pits at surface. Should the well intersect an overpressured unit any influx of formation fluids will cause an increase in the total volume of fluids in the well which results in a gain of drilling mud in the mud pits. At the same time the flow rate of mud returning to the mud pits (as recorded by the flow paddle) will also increase.

A reduction in the mud weight on its return to surface is a further indication of the intersection of overpressured formations. The temperature of the drilling mud is recorded both before entering the hole and upon its return to surface. Mud returning from an overpressured unit has a higher temperature than that returning from a normally pressured formation.

Geological indicators

Various techniques for the analysis of formation cuttings have been used to detect evidence of abnormal pressure. Where a zone of high pore pressure exists within an argillaceous sequence, it exhibits different properties from that of a normally compacted sediment. The increased pore pressure value results in a relatively high porosity which will be occupied by water. The rock will therefore have a lower bulk density. Shale bulk density, measured in gm/cc, is monitored closely during drilling, with decreasing density indicating increasing pressure (Fig. 3). Often a decreasing shale density trend can indicate that the well is approaching an overpressured formation. This is the transition zone (see overpressure indicators).

The shale factor is a further measurement made at the wellsite which may indicate overpressure. The shale factor is a measure of the cation exchange capacity (CEC) of the clay minerals in a rock. The CEC will decrease as clays convert from montmorillonite to illite in response to increasing temperature and pressure. Pure montmorillonite clays have a CEC of approximately 100 meq/100g; pure illites show no swelling characteristics and have 10–40 meq/100g. Of the most common clay types only the smectite group (including montmorillonite) has an affinity for water. Thus any rock unit that contains montmorillonite will have an affinity for water in an amount proportional to the montmorillonite content. This will be shown by a proportional value of shale factor. Immature sediments will be high in montmorillonite and will accordingly have a high shale factor. Similarly, compaction disequilibrium will also give rise to a high shale factor because diagenesis restricts the efficiency of the dewatering mechanism, resulting in clays with a high montmorillonite content. If however the overpressured zone is caused by montmorillonite dehydration, a low shale factor will be recorded because the montmorillonite will have altered to illite. This alteration process releases water into pore spaces which may not be able to escape, thereby inducing overpressure.

In summary, it can be stated that although shale factor cannot be used as an indicator of overpressure, it can be used to delineate between compaction disequilibrium and montmorillonite dehydration as the major overpressure mechanism.

Drill cuttings produced from an overpressured formation are invariably large and rounded and are produced by high pore pressures sloughing (collapsing into) the formation into the well bore.

Gas levels extracted from the returning drilling mud are also extremely important overpressure indicators. In situations where the well is approaching under-balance, the movement of the drill string up and down the well can draw gas into the well bore. These small but significant gas influxes will be recorded as gas peaks above the background gas levels when the mud is returned to surface. Drilling operations causing such influxes occur when the drill string is lifted off the bottom of the well during the connection of a further length of drill pipe to the drill string. The gas released is known as connection gas.

A similar situation occurs when the entire drill string is tripped out of the well when the BHA has to be changed, the lifting of the string drawing in gases. This is termed trip gas and is invariably represented by greater volumes of gas than connection gas.

### Petrophysical indicators

On the completion of drilling it is normal practise for a suite of petrophysical logs to be run in order to measure the acoustic, electrical and nuclear properties of the formations encountered in the well. Interpretation of pressure conditions from petrophysical logs is a qualitative process involving the establishment of trend lines for normal compaction (and pressure) in mudstone sections. Departures from the trend line may indicate abnormal pressures. However, such factors as hole condition, special formation characteristics and tool calibration or malfunction must be taken into account when interpreting pressure conditions from well logs. Overpressure is indicated by decreasing sonic values, decreasing density (as indicated by the nuclear logs), and decreasing resistivity.

The last decade has seen the development of numerous methods of obtaining petrophysical information from formations instantaneously during drilling. The forerunner of this is the measurement whilst drilling (MWD) technique. A gamma and sonic tool was placed within the BHA as close as possible to the drill bit. Measurements are transmitted to surface either through the metal of the drill pipe or via telemetry using the drilling mud as the transmission medium, to provide an almost instantaneous recording of gamma and sonic properties of the formation only a short distance above the drill bit. This method has now been evolved to provide the full suite of petrophysical properties, i.e. logging whilst drilling (LWD).

Should there be zones in which the presence of hydrocarbons is suggested by drilling and logging results, a repeat formation tester (RFT) tool may be run. This tool physically samples the formation fluids to investigate the pressure regime of the reservoir interval. Once the tool is packed-off against the sidewall of the well a valve is opened and formation fluids flow into the tools sample chamber, allowing for a continuous recording of formation pressures to be made for the duration of the test (Schlumberger Education Series, 1987).

**Indications of overpressure offshore southern West Greenland**

The pressure indicators in the five offshore exploration wells suggests that in general sediments deposited in West Greenland basins have attained normal pore pressures. However, in the two wells that drilled thicker sedimentary sections, Kangâmiut−1 and Ikermiut−1, overpressure was recorded within the Paleocene and Cretaceous formations. These two wells also intersected the only indications of both source rocks and generated hydrocarbons offshore West Greenland.

Sources of information concerning the pressure regime in West Greenland include daily wellsite reports, well completion reports and a full range of petrophysical logs from each of the five wells. A less comprehensive data set is available for the onshore boreholes.

Nukik–1

Well Nukik–1 was drilled by Mobil Exploration Greenland (Completion Report Nukik–1, 1977). The lithologies intersected at the wellsite are interbedded sandstone and siltstone with the well finally bottoming in Precambrian basement at a total depth of 2363 m (Fig. 4). No kicks were taken and no gas influxes were recorded during the drilling of the well, suggesting that the well was normally pressured and was drilled with a balanced mud system.

The absence of thick mudstone units prevented the estimation of an accurate Dc-exponent trend (Adams & Brown, 1977a). A suggested trend line is one that gives Dc-exponent values of 0.74 at 914 m and 1.10 at 2133 m and is very likely to represent a normal pressure gradient of 1.07 SG MWE.

Background gas levels were low throughout the drilling of the well, averaging 8 units (1 unit is equivalent to 200 ppm methane in air), over the depths 452 m to 1127 m and dropping to an average of 3 units from 1127 m to total depth at 2363 m. Maximum gas levels recorded were 27 units at 649 m. No connection gas was recorded at any time during drilling and maximum trip gas recorded was 8 units at 580 m.

Mud temperature was recorded before entering the borehole and on returning to surface. Measurements show that stable conditions were maintained throughout the well with no abnormal deviations from the trend line.

The lack of firm mudstone prevented any pressure estimates to be made from cuttings and the shale density. However shale factor measurements were made on the clay fractions of siltstones and the values recorded range from 8 to 15 milli-equivalents per 100 grams (no plot available). These values indicate a normally pressured environment. Values of 12 to 15 milliequiv/gm at a depth of 1981 m could indicate overpressure but they are most likely due to the production of montmorillonite during the diagenesis of volcanic and basement rocks which commonly occur in the area of the Nukik Platform.

Analysis of the Schlumberger sonic, resistivity and nuclear logs also suggests that the well was normally pressured. Very minor deviations from trend lines occur over the intervals 1280 m to 1494 m and 1889 m to 2103 m.

The lack of any significant deviations in monitored parameter trends suggests that the formation pore pressure throughout the well is equal or nearly equal to the normal pressure gradient, i.e. 1.07 to 1.09 SG MWE.

Nukik–2

Well Nukik–2 was drilled by Mobil Exploration Greenland 11.6 km due north of Nukik–1 (Completion Report Nukik–2, 1977). Lithologies intersected were dominated by silty sandstones with thin mudstone interbeds (Fig. 5). Below a depth of 2133 m mudstones were intersected (these mudstones were not intersected in Nukik–1). The well finally bottomed in basaltic lava flows of Paleocene age at a depth of 2694 m. No kicks were taken during drilling and gas levels remained low, and it can therefore be concluded that pore pressures are normal in the area of Nukik–2.

The difficulties encountered in establishing a reliable Dc-exponent trend in Nukik–1 were similarly experienced in Nukik–2, reflecting the predominance of arenaceous lithologies (Adams & Brown, 1977b). In such circumstances the Dc-exponent is a poor indicator of abnormal pressures.

Gas levels remained low throughout the drilling of the well, with background gas averaging 5 units to a depth of 1128 m and between this and total depth gas levels fell to an average of 3 units. Maximum background gas recorded was 10 units at a depth of 620 m. No connection gases were recorded and trip gases were below 10 units.

The monitoring and recording of mud temperatures did not indicate any deviations from a normal trend line.

The cuttings obtained from the mudstones intersected below 2133 m gave no indications of overpressure, i.e. the cuttings were not overly large in size, and they did not slough or cave into the well. However, following two days of drilling within the basalt section at the base of the well, these mudstones began to cave and "tight hole" (increased torque values) conditions were experienced at a depth of 2669 m when pulling the drill string out of the hole. The tight hole and shape of cuttings may indicate a degree of overpressure. However, other points worthy of note in connection with this tight hole are i) there had been no wiper trip to clean the hole for 56 hours, ii) the stabilisers within the drill-string were caked (balled) with mudstone, and iii) the Schlumberger tool experienced no problems over this depth when running to bottom. The calliper log also indicates a widening of the hole at this depth rather than a narrowing. Thin sandstone interbeds did not kick and gas levels were low over the depth of the tight hole. Consequently, the tight hole is thought to be the result of the stabilisers becoming balled with mudstone and the long period since cleaning the hole with a wiper or bit trip.

The shale (bulk) density shows a decrease from 2.0 gm/cc to 1.85 gm/cc below a depth of 1981 m. This decrease is attributed to an increase in organic matter in the mudstones rather than to an increase in pressure.

The shale factor values obtained in Nukik–2 range from 5 to 20 milliequiv per 100 gm, with an average of 10 milliequiv per 100 gm. Below a depth of 2377 m there is a marked increase in this value to 20 milliequiv per 100 gm which is attributed to the creation of montmorillonite by the breakdown of basaltic rock fragments. The Nukik Platform is an area of predominantly basic lavas and basement rocks.

Both the Schlumberger sonic and resistivity logs trends are offset below a depth of 1524 m and the sonic log shows a second decrease at a depth of 2377 m. This is also confirmed by the nuclear logs. These responses may indicate overpressure, but could also be the result of increased organic content which is supported by the darker colour of the mudstones below 2377 m.

The pore pressures in Nukik–2 appear to be normal to a depth of 1524 m, i.e. 1.07 SG MWE. The sonic and resistivity logs may indicate overpressure below this depth but the lack of any other indicators of overpressure suggests that pressures are in fact normal. Over the depth interval 2377 m to 2553 m there are deviations in the trend of the shale density, shale factor, sonic, resistivity and calliper logs which may indicate overpressure. However the absence of any connection gas when using a relatively low mud weight (1.13 to 1.16 SG) and the lack of large rounded cavings do not indicate overpressure.

In spite of these conflicting lines of evidence it is concluded that the pore pressure was normal throughout the entire well, with a value of 1.07 SG MWE; however the possibility remains that there are abnormal pressures below 2377 m, with a pore pressure of 1.12 SG MWE.

Hellefisk–1

Well Hellefisk–1 was drilled by ARCO Greenland Incorporated to test a large faulted anticline truncated by a regional unconformity (Well Completion Report, 1978). Lithologies intersected include Middle Eocene to Pliocene sandstone and shales overlying a predominantly Paleocene shale interval, with the well intersecting Paleocene basalts at a depth of 2505 m (Fig. 6). The well continued to drill lavas until termination of drilling at a depth of 3201 m. No indications of overpressure were encountered in the well.

The predominantly sandstone interval intersected during the drilling of the 17 1/5" hole (446 m to 1780 m), prevented establishment of a reliable Dc-exponent trend (Core Laboratories Inc., 1977). Mild to severe lost circulation problems were experienced in this section (drilling fluid being lost to the formation) probably due to the unconsolidated nature of the sandstones. The pore pressure was calculated to be in the range 1.02 to 1.05 SG MWE, so this section was drilled somewhat overbalanced with a mud weight of 1.08 SG. The unconsolidated nature of the lithology resulted in the mud containing large amounts of cuttings which may also have increased the rate of mud loss. During the drilling of the predominantly mudstone section over the depth range 1780 m to 2505 m, a Dc-exponent trend was established at 1.06 SG MWE. The lost circulation problem decreased during the drilling of these more compacted mudstones. The Dc-exponent trend does not indicate the presence of overpressure. Upon intersection of the basalts, the Dc-exponent trend shifted to the right and this new trend was maintained to total depth. However since the Dc-exponent defines a compaction trend in sedimentary rocks, the trend line established in the basalts is almost meaningless.

Gas levels recorded during drilling were very low with a maximum of 42 units recorded at a depth of 558 m. Trip gases were also very low with a maximum of 15 units recorded at a depth of 1225 m. No connection gases were recorded in the well.

The mud temperature gradient shows no abnormal trends. However a higher mud temperature trend was recorded during the drilling of the basalts which can be attributed to either slower drilling rates or to the basalts having a higher thermal heat flow.

Measurement of shale density was performed only at irregular intervals, due to the lack of thick mudstone intervals. A reliable trend of shale density could not therefore be defined.

In conclusion, the absence of any abnormal trends in any of the pressure indicators suggests that well Hellefisk–1 is normally pressured throughout.

Ikermiut–1

Well Ikermiut–1 was drilled by Chevron Petroleum Company of Greenland and was a test of a large anticlinal fold with significant closure within the Eocene and Paleocene section (Final Geological and Drilling Report, 1977). The upper section of the well to a depth of 1530 m is dominated by interbedded sandstone and siltstone. Below this the lithology is predominantly mudstone with the well finally bottoming in Campanian mudstones at a depth of 3619 m (Fig. 7). Indications of abnormal pressure were initially encountered at a depth of 2160 m conforming to the first intersection of gas-prone source rocks.

The estimation of a reliable Dc-exponent throughout the drilling of the interbedded sandstone and siltstone unit (460 m to 1535 m) was not possible (Debruyst, 1977). However below this depth, over the interval 1535 m to 2160 m, a succession of Eocene mudstones was intersected which allowed the establishment of a normal compaction trend for the Dc-exponent (Fig. 3). Below a depth of 2160 m the Dc-exponent exhibits a marked cut-back and the establishment of a new trend.

A leak-off test performed at a depth of 2710 m, below the 9 5/8" casing shoe, established a fracture gradient of 2.84 SG MWE, and pore pressure was calculated to be 1.26 SG MWE. At this point a change in the Poisson coefficient was introduced by the pressure engineer at the wellsite and this induced a leftward shift in the Dc-exponent curve.

A further change in the Dc-exponent trend is seen at a depth of approximately 3175 m. The trend line exhibits a marked shift to the left suggesting a further increase in the pore pressure gradient. Calculated pore pressure is 13.10 ppg at a depth of 3620 m. This trend was maintained to total depth at 3619 m.

Mud weights (Fig. 7) were increased from an average of 1.13 SG to an average of 1.31 SG below the 9 5/8" casing shoe following the results of the leak-off test performed at a depth of 2710 m.

Gas levels were generally low in the upper section of the hole, but a marked rise in background, connection and trip gases was recorded from a depth of 2135 m. TOC values in the mudstones also rise below this depth to an average of 1.43% and the mudstones are predominantly gas prone. This conforms to the onset of the overpressured section of the well. At a depth of 2815 m a further rise in TOC value to a maximum of 2.83% was recorded, a little below the intersection of Cretaceous mudstonesat a depth of 2743 m. Background gas levels averaged 1% to 2% with connection gas peaks reaching up to 2% above background. Trip gas values consistently averaged 30% and the gas was composed predominantly of methane.

Shale density measurements indicate an average density of 2.28 g/cc over the depth interval 2710 m to 2960 m, after which a small departure from the trend line was identified. At a depth of 3550 m the shale density was recorded as being 2.30 g/cc.

Indications of overpressured formations were also provided by drill cuttings. A narrowing of the well bore imparted high torque values onto the drill string at a depth of 3128 m which was overcome by repeated reaming of the hole to a depth of 3172 m. The cuttings from this section were large and curved which is indicative of sloughing formations resulting in a narrowing of the well bore. A further indication of under-gauged hole was recorded at a depth of 3245 m and again the drill cuttings were large and curved on their return to surface.

The results of the petrophysical logging also indicates overpressured intervals. Analysis of the sonic log (Fig. 7) demonstrates the deviation from a normal trend line at a depth of 2160 m. A shift to the left indicates a slower interval transit time of sound through a formation which is what is expected from an overpressured formation.

The FDC (Compensated Formation Density Tool) log demonstrates a clear deviation from the trend line. The zones of undercompaction identified between 2140 m to 2260 m also correspond to the onset of overpressure identified on the sonic and Dc-exponent curves. A second zone of overpressure can be identified between 2745 m and 2800 m. A third zone of low density can be seen over the depth range 2960 m to 3140 m where the shale density falls from 2.42 g/cc to 2.25 g/cc. This corresponds to the interval of under-gauge hole and high torque values experienced over the depth range 3128 m to 3178 m.

In conclusion, well Ikermiut–1 experienced normal pore pressures to a depth of 2160 m at which point the onset of overpressure is indicated by a rise in both gas and TOC values, and a cut-back in the Dc-exponent, sonic and FDC log trend lines (Fig. 7). A further increase in TOC and gas values was also recorded at a depth of 2815 m and may also be identified on the sonic curve. At no point during the drilling of the well did these pressures prove great enough to be hazardous to drilling and were efficiently controlled with the use of an appropriate mud system.

Kangâmiut–1

Well Kangâmiut–1 was drilled by Total Grønland Olie to test Lower Tertiary, Cretaceous and pre-Cretaceous sediments within closure on the western flank of a basement high known as the Kangâmiut Ridge (Manderscheid & Quin, 1977). The well intersected Tertiary sandstones and mudstones before drilling through a fault flanking the ridge and bottoming in basement at a depth of 3874 m (Fig. 8). There are strong indications for the presence of overpressured formations near the base of the well as indicated by the taking of a gas kick, mud weights required to re-establish control of the well, analysis of shale density measurements and decreasing trend of the sonic log. This well intersected the only occurrence of hydrocarbons as yet encountered offshore West Greenland.

Due to the non-availability of a pressure report for Kangâmiut–1, a complete pressure analysis for the entire well is not possible. However integration of the daily wellsite reports, the summary of operations (Manderscheid & Quin, 1977) and well logs do provide a clear understanding of the formation pressures intersected over the relevant interval of the well, along with a summary of shallower intervals.

From the sea bed to a depth of 1540 m drilling, mud and logging parameters indicate normally pressured formations. The ROP was consistent with increasing depth, gas levels remained very low, and shale density measurements recorded in this predominantly arenaceous interval follow a normal compaction trend, averaging 2.05 g/cc (Fig. 8).

Below this depth indications of overpressure began to be recorded. Over the depth range 1540 m to 1714 m (Oligocene silty sandstone) overpull of up to 30 tons was required to free the drill pipe from the sidewall of the hole. This suggests that the formation was swelling into the annulus and trapping the drill pipe.

At a depth of 2550 m overpull of 20 tons was required to free stuck pipe. Below 2550 m the shale density plot began to deviate from the normal trend line and there was a rise in the temperature of drilling mud returning from the well. The sonic log also indicates a deviation from this depth. Below a depth of 2580 m background gas levels began to rise to an average of 1.5% (predominantly methane). The apparent absence of any connection and trip gases suggests that the well was drilled with a balanced mud system (1.17 SG to 1.22 SG).

At a depth of 2625 m a change from Upper Eocene and younger silty sandstones to mudstones and claystones of mid-Eocene age was recorded. The decreasing trend in shale density and sonic values was maintained over this interval as was the increasing gas and mud temperature levels.

At a depth of 2740 m (Lower Eocene), the shale density plot (Fig. 8) shows an abrupt decrease from an average of 2.05 g/cc to an average of 1.85 g/cc. This steadily decreasing trend is maintained to the final shale density measurement at a depth of 3670 m with values averaging a minimum of 1.7 g/cc. Gas values also rise to an average of 2% and mud temperatures maintain the higher trend.

The daily wellsite reports note the presence of hyperhydrated (undercompacted) shales over the interval 2730 m to 2950 m with overpull of 30 tons at a depth of 2872 m. It was then decided to log the hole and to then run and set the 9 5/8" casing. The 9 5/8" casing shoe was set at a depth of 2935.2 m.

A leak-off test was performed at a depth of 2995 m with injection of mud into the formation beginning at 415.26 kg $cm^{-2}$ $m^{-1}$ (1800 psi) or 1.77 SG MWE (14.77 ppg). The weekly operations report concluded that 1.77 SG should be the maximum equivalent specific gravity allowed while drilling 8 1/2" hole. The mud weight was increased to 1.32 SG for drilling of the next section of hole. The increased mud weight probably accounted for the relatively small decrease in background gas values to 1.5% below the casing shoe.

During the drilling of the 8 1/2" hole further indications of overpressure were identified. A decrease in the gauge of the hole was evident in the depth range 3200 m to 3250 m and overpull of greater than 40 tons was recorded over the interval 3010 m to 3070 m during a short wiper trip to the 9 5/8" casing shoe. This narrowing of the hole prevented the efficient retrieval of the pipe and it required 40 tons of pressure to free the string. To counteract this the mud weight was steadily increased to 1.42 SG.

Drilling progressed through a predominantly shaley interval with a steadily decreasing ROP, from 10 min/m to 15 min/m from a depth of 3500 m, and gas levels averaging 1.0%, the gas consisting mostly of methane but with traces of C2 (ethane), C3 (propane) and C4 (butane).

At a depth of approximately 3704 m a drilling break occurred when the ROP increased from 10 min/m to 4 min/m. At a depth of 3706 m a flow-check was performed. Drilling and circulation was stopped to investigate if mud was flowing back into the mud pits due to pressures in the formation rather than because of mechanical pumping. A mud gain of 1 $m^3$ was recorded and the well was then closed-in, i.e. the pipe-rams were closed around the drill pipe to prevent uncontrolled flow of the influx up the annulus. Circulation was resumed and the formation fluids circulated through the choke manifold. Gas levels of 9% total gas were recorded (C1 7%, C2 0.23%, C3 0.12%, C4 0.03%) confirming that a gas kick had been taken (Geoservices Mud Log, 1976 and Manderscheid & Quin, 1977). This gas was burned-off using the drilling derrick gas flare.

The lithology of the formation over which the drilling break occurred consists of medium- to coarse-grained, sub-angular to rounded feldspathic sandstone intercalated with thin black shale. This sandstone interval has been termed the Narssarmiut Formation (Rolle, 1985).

To control the increased formation pressure the mud weight was raised from 1.42 SG to 1.67 SG and circulated repeatedly at the 9 5/8" casing shoe to condition the mud. During this circulation the mud was degassed via the degasser and flared-off. The hole was re-opened and another flow check performed which proved negative. The string was then lowered to a depth of 3689 m. During this circulation the drill string became stuck and circulation was lost. The pipe was eventually freed with 60 tons of overpull. Another flow-check showed that the well was again flowing and the well was closed in. Circulation was resumed through the choke manifold. On re-opening of the well the string was pulled to the shoe and attention paid to filling the drill pipe with mud to prevent swabbing as each section of drill pipe was retrieved.

The string was then lowered into the well and the hole reamed repeatedly to bottom to bring it back into gauge. Reaming was very difficult over the interval 2990 m to 3185 m with the bit eventually balling. A new bit was attached to the string and reaming resumed. Over the interval 3616 m to 3633 m the string became repeatedly stuck. The returning drilling mud indicated that gas was flowing into the well from the interval 3673 m to 3704 m, requiring degassing of the mud.

Upon completion of reaming, new hole was drilled from a depth of 3730 m to 3767 m. The daily wellsite reports describe the formation as consisting of quartzo-feldspathic sandstones which are porous and gas-charged over the interval 3673 m to 3725 m but becoming tighter with depth, and intercalated with black shale. Hole conditions were reported to be very difficult especially in the overlying shale interval, with caving and narrowing of the hole. At this depth the well was logged. During the logging a second kick was taken and a 4 $m^3$ gain in the mud pits recorded. The Schlumberger tool was retrieved from the well and a heavy mud weight of 1.85 SG (kill mud) circulated to stabilise the well. During this conditioning the mud was degassed continually. Drilling recommenced upon stabilisation using a mud weight of 1.72 SG.

Drilling continued to a depth of 3777 m through lithologies that have been variously described as feldspathic sandstone, weathered basement, or either of these in a fault zone; at this point further logging was successfully completed. Drilling resumed with the mud weight maintained at 1.72 SG and continued to a depth of 3870 m (depth quoted in the daily wellsite report). The formation was cored over the interval 3870 m to 3874 m and 4 m of basic intrusive was recovered. At this point it was decided to terminate further drilling. The 7" liner was set at a depth of 3855.5 m and cemented in.

A Drill Stem Test (DST) was performed over the porous gas charged sandstone section. The 7" liner was perforated over the interval 3674 m to 3705 m. Pressure readings recorded an initial formation pressure of 500 kg (7113 psi) which was maintained for 1 1/4 hours with a flow rate of 7.5 $m^3/h$, after which pressure declined. A total of 29 $m^3$ of fluid was recovered via reverse circulation. Chemical analysis of the fluids suggests that they have similar characteristics to those of the drilling mud. It is likely that the great length of time and the methods needed to stabilise the hole (repeated reaming, circulating and tripping) over the difficult overpressured section, resulted in drilling mud invading the formation. It is not unlikely that it was these fluids that were recovered during the test.

It was concluded that the water samples are not representative of the formation water (Manderscheid & Quin, 1977). The implication of this is that the gas reservoired in the sandstones over the interval of the DST was not recovered and that the prospectivity of the Kangâmiut Ridge was therefore not adequately tested by the well.

**Indications of abnormal pressure onshore West Greenland**

The sources of data relating to the pressure regime of rocks onshore West Greenland are much less comprehensive than those from the offshore area and are limited to the shallow drilling programme for Cretaceous coals on the Nuussuaq peninsula in 1980 (Shekhar *et al.*, 1980, 1982). A total of three boreholes were drilled, two of which were abandoned before reaching a depth of 200 m but one successfully reached 566 m.

An Albian to Danian sedimentary basin up to at least 8 km thick extends from Disko Bugt northwards through Nuussuaq to Svartenhuk Halvø (Henderson *et al.*, 1976; Pedersen & Pulvertaft, 1992; Christiansen *et al.*, 1995). The exposed Cretaceous section consists of fluviatile clastics in the south changing to marine mudstones in the north reflecting the change from upper delta plain in the south to deeper water prodelta muds in the north (Fig. 9). Transport direction was from south-east to north-west. Coal seams averaging 1 m thick are relatively common within this deltaic succession. Towards the end of the Maastrichtian the area became tectonically unstable. Phases of uplift were followed by incision of valleys in the underlying sediments. Conglomerates and both turbiditic and fluvial sands and mudstones of Late Maastrichtian to middle Paleocene age filled the valleys, while on the fault-controlled slope to the west more than 2.5 km of turbidite sands alternating with marine mudstones were deposited (Dam & Sønderholm, 1994).

Longyear Canada Inc. performed the drilling using a '44' drilling rig. The drilling fluid was a mixture of water, calcium chloride and zoegal mud. Calcium chloride was used to counteract the permafrost, which did not allow the use of a normal bentonite mud system. Zoegal mud (a viscosifier) was used to facilitate the recovery of cuttings.

Numerous porous and friable sandstones were intersected which resulted in lost circulation of the drilling fluid. An added problem was that the formation caved into the borehole and could not be washed away, leading to the jamming of the drill string. The zones of lost circulation were plugged using Kwikseal but two of the boreholes were abandoned at depths of 103 m and 175 m respectively due to these problems. A possibly more significant pressure indicator was the intersection of thin swelling clay bands which increased torque levels on the drill string.

In August 1993 the Petro Drilling Company Ltd Canada were contracted by the Geological Survey of Greenland (GGU) to sink a borehole on the south-west coast of the Nuussuaq peninsula at Marraat. The aim of the borehole was to investigate the discovery in 1992 of oil-impregnated vesicles in Lower Tertiary basalts (Christiansen *et al.*, 1993). This discovery was not a surprise, since highly coalified bitumen had been located earlier only a few kilometres away. Laboratory analysis of the oil suggests an Early Tertiary (or latest Cretaceous) age of the source rock and that the oil has undergone no thermal alteration and minimal biodegradation.

A total depth of 446.85 m was reached using a wireline diamond drilling system before the borehole was abandoned due to technical problems (Christiansen *et al.*, 1993; Dam & Christiansen, 1994). A porous zone in the uppermost 86 m of the basalts contained liquid oil. Further work is in progress to investigate the oil seep but the implications of the Marraat discovery are very encouraging for exploration offshore West and North-West Greenland. During drilling of the borehole quantities of highly saline water under high pressure was seen to flow from the hole. Unfortunately no pressure measurements were recorded during drilling.

**Prediction of overpressure in southern West Greenland**

The wide spacing of the wells drilled both offshore and onshore does not provide the amount of information necessary to arrive at an accurate model for the pressure regime of the West Greenland basins. However the interpretation of seismic data and its integration with the limited well information does provide information concerning the configuration and development of the offshore West Greenland basins. Assumptions relating to anticipated formation pressures can be made based on expected litholgies, depositional environments, and the tectonic history of the area.

The substantial thickness (up to at least 8 km) of Cretaceous and Lower Tertiary fluvio-deltaic and prodelta sediments exposed onshore West Greenland in the Disko–Nuussuaq–Svartenhuk Halvø area (Pedersen & Pulvertaft, 1992) means that this area is likely to have overpressured formations at some point in the subsurface. Deltaic sediments often have overpressured units due to the entrapment of rapidly deposited sand bodies within thick mudstone intervals. This results in a number of isolated sand bodies each with its own local pressure regime. The possibility that such an overpressured sand unit could be intersected should a borehole be drilled in the area must be taken into account.

There is also field evidence to suggest that this area has experienced uplift which may further enhance any abnormal pressures. The sediments are overlain by a thick succession of Tertiary basalts which are related to the initiation of sea-floor spreading of the Labrador Sea during the Early Paleocene. The lowermost basalts consist of hyloclastite breccias and pillow lavas that build up large, delta-like structures up to 700 m thick which wedge towards the east and south-east (Pedersen & Dueholm, 1992). These basaltic lavas were extruded at or very close to base level where they subsequently flowed into a body of water, either marine or a lake, and chilled to form breccias and pillows which tumbled down into the water body. Today the upper surfaces of these breccias are at an elevation of more than 1000 m, indicating uplift of at least a similar amount. By implication the underlying deltaic sediments also have experienced the same degree of uplift. The possibility that they may retain a pressure regime stable at greater depths than their present elevation must not be overlooked.

A further area of uplift has been identified on seismic data offshore and is associated with the Ungava Fault Zone. This is a major north-north-east trending zone of strike-slip faulting extending from an area west of Ikermiut–1, to the north-western tip of the Nuussuaq peninsula where a splay is represented by the Itilli Fault. Transpressional movement along this fault system, most probably during the Eocene (Klose *et al.*, 1982; Chalmers *et al.*, 1993), led to the creation of the Davis Strait High and has deformed Cretaceous and Lower Tertiary sediments into very large flower structures in the area west of Ikermiut–1. This deformation probably raised rocks with a pore pressure developed at greater depths to shallower levels in the crust. Such a situation is evident in well Ikermiut–1 where the increase in pore pressure below a depth of 2160 m is directly related to the intersection of uplifted Paleocene and Cretaceous mudstones with TOC $\geq$ 2%.

Another scenario where overpressured formations may prove hazardous to drilling is where turbidite fans have been deposited in deep water. The rapid introduction of shallow marine clastics into deeper water and their burial by deep marine clays can prevent the sandstones dewatering and equalising their pressure regime. Such fans have been identified on seismic data within Upper Cretaceous and Paleocene sequences which are known to have overpressured formations associated with them elsewhere in the basin, such as in well Kangâmiut–1.

Overpressure may also be associated with prospects with targets consisting of syn-rift sandstones which have been faulted to form large rotated fault blocks. The crests of the fault blocks may have been rotated to a level shallower than they previously had been. These sandstones became sealed by mudstones. This sort of play has been identified in the area of the Fylla Structural Complex situated 130 km offshore from Nuuk (Bate *et al.*, 1994).

**Summary and conclusions**

The limited well control over such a large area as offshore southern West Greenland limits the understanding of the complex nature of abnormal pressures within the basin. However, the integration of the seismic and the limited well data can provide a moderate level of understanding of the basin geometry and its structural history. This in turn allows for an estimation of the pressure regimes within the basin.

Three of the five wells, Nukik–1, Nukik–2 and Hellefisk–1, intersected predominantly sandy Tertiary formations before bottoming in either basement or basaltic lava flows. None of these wells displays any distinct evidence of abnormal pressure. However, two of the wells, Kangâmiut–1 and Ikermiut–1, show evidence of overpressure within the Paleocene and Upper Cretaceous successions. In both of these wells a rise in both the source rock potential and gas levels are associated with the onset of overpressure. In Kangâmiut–1 the intersection of an overpressured sandstone has provided the only showing of hydrocarbons found so far in the offshore West Greenland basins.

The evidence from the five wells suggests that the predominantly sand-prone Tertiary formations are normally pressured. However the Paleocene and deeper formations appear to exhibit overpressured intervals which have proved both problematic and costly to control. Further exploration drilling should make provision for the intersection of overpressured units in areas where the target consists of sediments deposited under conditions of rapid deposition and where there is evidence of structural uplift.

*Acknowledgements.* I would like to thank Chris Pulvertaft and Flemming Christiansen for editing the text. I would also like to thank Jan Escher for translating sections of French text. Finally thanks are due to Carsten Thuesen and Jetta Halskov for production of figures.

**References**

Adams, P. & Brown, D 1977a: Pressure evaluation service report of Nukik–1. Exploration logging services. 14 pp. Released industry report GGU archive.

Adams, P. & Brown, D. 1977b: Pressure evaluation service report of Nukik–2. Exploration logging services. 11 pp. Released industry report GGU archive.

Barker, C 1972: Aquathermal pressuring – role of temperature in the development of abnormal pressure zones. *Bull. Amer. Ass. Petrol. Geol.* **56**, 2068–2071.

Bate, K. J., Whittaker, R. C., Chalmers, J. A. & Dahl-Jensen, T. 1994: Fylla complex – possible very large gas reserves off S. W. Greenland. *Oil & Gas Journal.* **92/34**, 79–82.

Burst, J. F. 1969: Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration. *Bull. Amer. Ass. Petrol. Geol.* **53**, 73–93.

Chalmers, J. A. & Pulvertaft, T. C. R. 1993: The southern West Greenland continental shelf – was petroleum exploration abandoned prematurely? *In* Vorren, T. O. *et al.* (ed.) *Arctic geology and petroleum potential*, 55–66. Amsterdam: Elsevier for Norwegian Petroleum Society.

Chalmers, J. A., Pulvertaft, T. C. R., Christiansen, F. G., Larsen, H. C., Laursen, K. H. & Ottesen, T. G. 1993: The southern West Greenland continental margin: rifting history, basin development, and petroleum potential. *In* Parker, J. R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, 915–931. Geol. Soc. London.

Chevron Petroleum Company of Greenland 1977: Final geological and drilling report. Ikermiut–1. Offshore concession 28.

Christiansen, F. G., Dam, G. & Pedersen, A. K. 1993: Discovery of live oil at Marraat, Nuussuaq: field work, drilling and logging. *Rapp. Grønlands geol. Unders.* **160**, 57–63.

Clarke, D. B., & Pedersen, A. K. 1976: Tertiary volcanic province of West Greenland. *In* Escher, A. & Watt, W. S. (ed.) *Geology of Greenland*, 364–385. Copenhagen: Geological Survey of Greenland.

Core Laboratories Inc. 1977: Extended services well report of well Hellefisk–1 prepared for Arco Greenland Inc, 8 pp. Released industry report GGU archive.

Dam, G. & Christiansen, F. G. 1994: Well summary Marraat–1, Nuussuaq – West Greenland. *Open File Ser. Grønlands geol. Unders.* **94/11**, 26 pp., 7 app.

Dam, G. & Sønderholm, M. 1994: Lowstand slope channels of the Itilli succession (Maastrichtian–Lower Paleocene), Nuussuaq, West Greenland. *Sediment. Geol.* **94**, 49–71.

Debruyst J. P. 1977: T.D.C. Well summary report. Chevron petroleum Well: Ikermiut–1, 7 pp. Released industry report GGU archive.

Dickinson, G. 1953: Geological aspects of abnormal reservoir pressures in Gulf Coast Louisiana. *Bull. Amer. Ass. Petrol. geol.* **37,** 410–432.

Fertl, W. H., & Chilingarian, G. V. 1977: Importance of abnormal formation pressures to the oil industry. *J. Petrol. Tech.* **29**, 347–354.

Gretener, P. E. 1977: Pore pressure: fundamentals, general ramifications and implications for structural geology. *Amer. Ass. Petrol. Geol. Continuing Course Note Series* **4**, 87 pp.

Henderson, G. 1975: Stratigraphy and structure of the Tertiary volcanic rocks of the Marrait kitdlît area, Nûgssuaq. *Rapp. Grønlands geol. Unders.* **69**, 11–16.

Henderson, G., Rosenkrantz, A & Schiener, E. J. 1976: Cretaceous–Tertiary sedimentary rocks of West Greenland. *In* Escher, A. & Watt, W.S. (ed.) *Geology of Greenland*, 340–362. Copenhagen: Geological Survey of Greenland.

Hubbert, M. K. & Rubey, W. W. 1959: Overthrust belt in Geosynclinal area of western Wyoming in light of fluid pressure hypothesis. *Bull. Geol. Soc. Amer.* **70**, 167–206.

Hunt, J. M. 1990: Generation and migration of petroleum from abnormally pressured fluid compartments. *Bull. Amer. Ass. Petrol. Geol.* **74**, 1–12.

Klose, G. W., Malterre, E, McMillan, N. J. & Zinkan C. G. 1982: Petroleum exploration offshore southern Baffin Island, Northern Labrador Sea, Canada. *In* Embry, A. F. & Balkwill, H. R. (ed.) Arctic Geology and Geophysics. *Mem. Can. Soc. Petrol. Geol.* **8**, 233–244.

Magara, K. 1975: Reevaluation of montmorillonite dehydration as cause of abnormal pressure and hydrocarbon migration. *Bull. Amer. Ass. Petrol. Geol.* **59**, 292–302.

Manderscheid, G. & Quin, R. 1977: Well history report. TGA Grepco Kangâmiut–1, Total. 78 pp. Released industry report GGU archive.

Pedersen, A. K. & Dueholm, K. S. 1992: New methods for the geological analysis of Tertiary volcanic formations on Nuussuaq and Disko, central West Greenland, using multi-model photogrammetry. *In* Dueholm K. S. & Pedersen A. K. (ed.). Geological analysis and mapping using multi-model photogrammetry. *Rapp. Grønlands geol. Unders.* **156**, 19–34.

Pedersen, G. K. & Pulvertaft T. C. R. 1992: The nonmarine Cretaceous of the West Greenland Basin, onshore West Greenland. *Cretaceous Research.* **13,** 263–272.

Powers, M.C. 1967: Fluid-release mechanisms in compacting marine mudrocks and their importance in oil exploration. *Bull. Amer. Ass. Petrol. Geol.* **51**, 1240–1254.

Rolle, F. 1985: Late Cretaceous – Tertiary sediments offshore central West Greenland: lithostratigraphy, sedimentary evolution, and petroleum geology. *Can. J. Earth Sci.* **22**, 1001–1019.

Schlumberger Education Services 1987: Log interpretation principles/applications. Second edition. 145–146.

Shekhar, S. C., Frandsen, N. & Thomsen, E. 1980: Coal in West Greenland. *Rapp. Grønlands geol. Unders.* **105**. 38–41.

Shekhar, S. C., Frandsen, N. & Thomsen, E. 1982: *Coal on Nûgssuaq, West Greenland.* 82 pp. Copenhagen: Geological Survey of Greenland.

**Figure Captions**

1. Map showing the location of five offshore oil wells and of four onshore boreholes.

2. Schematic diagram of subsurface formation-pressure environment concepts (after Fertl & Chilingarian, 1977).

3. Diagram to show schematic response of drilling and geological indicators in zones of overpressure.

4. Pressure indicators for well Nukik–1.

5. Pressure indicators for well Nukik–2.

6. Pressure indicators for well Hellefisk–1.

7. Pressure indicators for well Ikermiut–1.

8. Pressure indicators for well Kangâmiut–1.

9. Generalised facies distribution with sediment transport direction for the Cretaceous rocks of central West Greenland (after Henderson *et al.*, 1976).

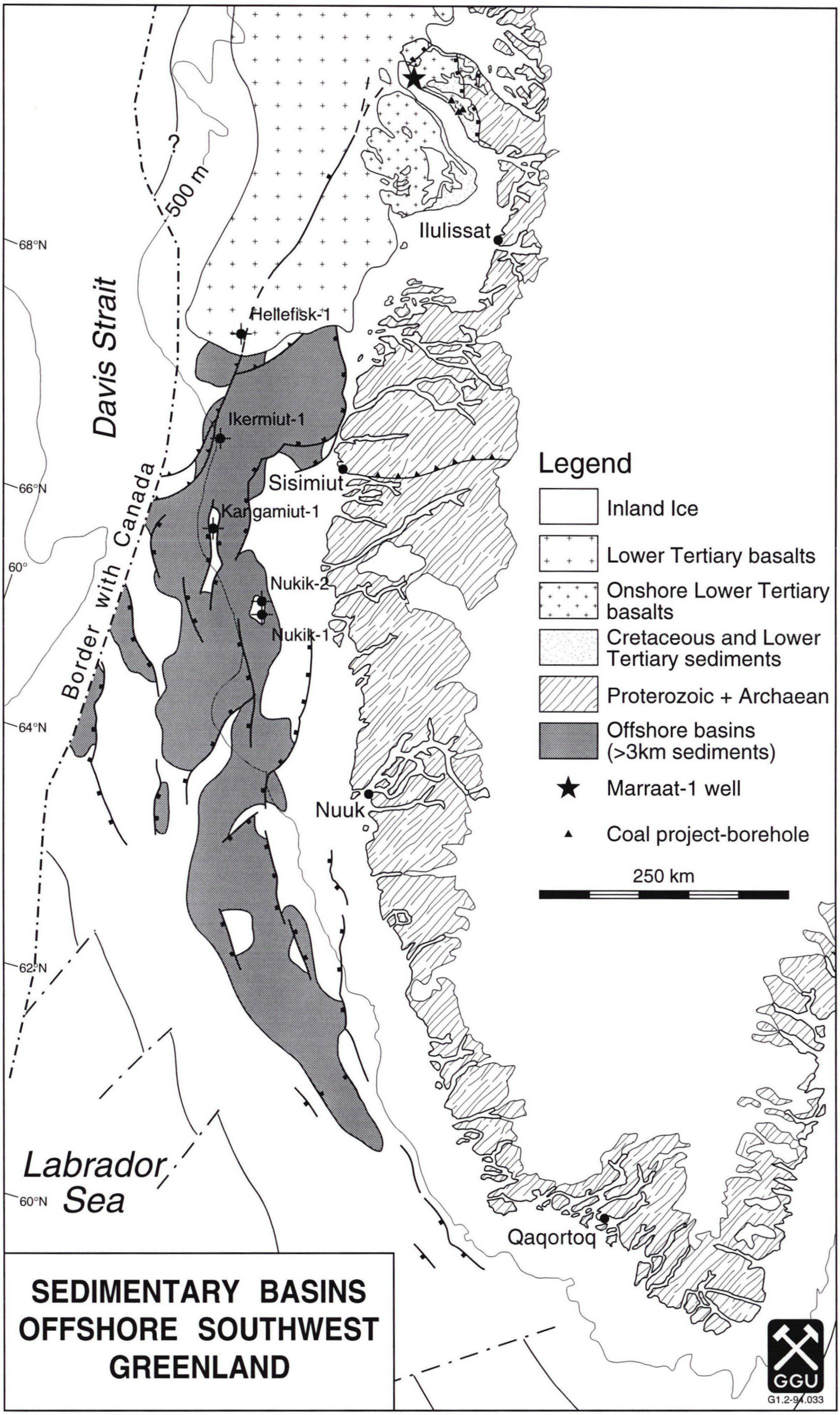



Fig. 1. Map showing the location of five offshore oil wells and of four onshore boreholes.

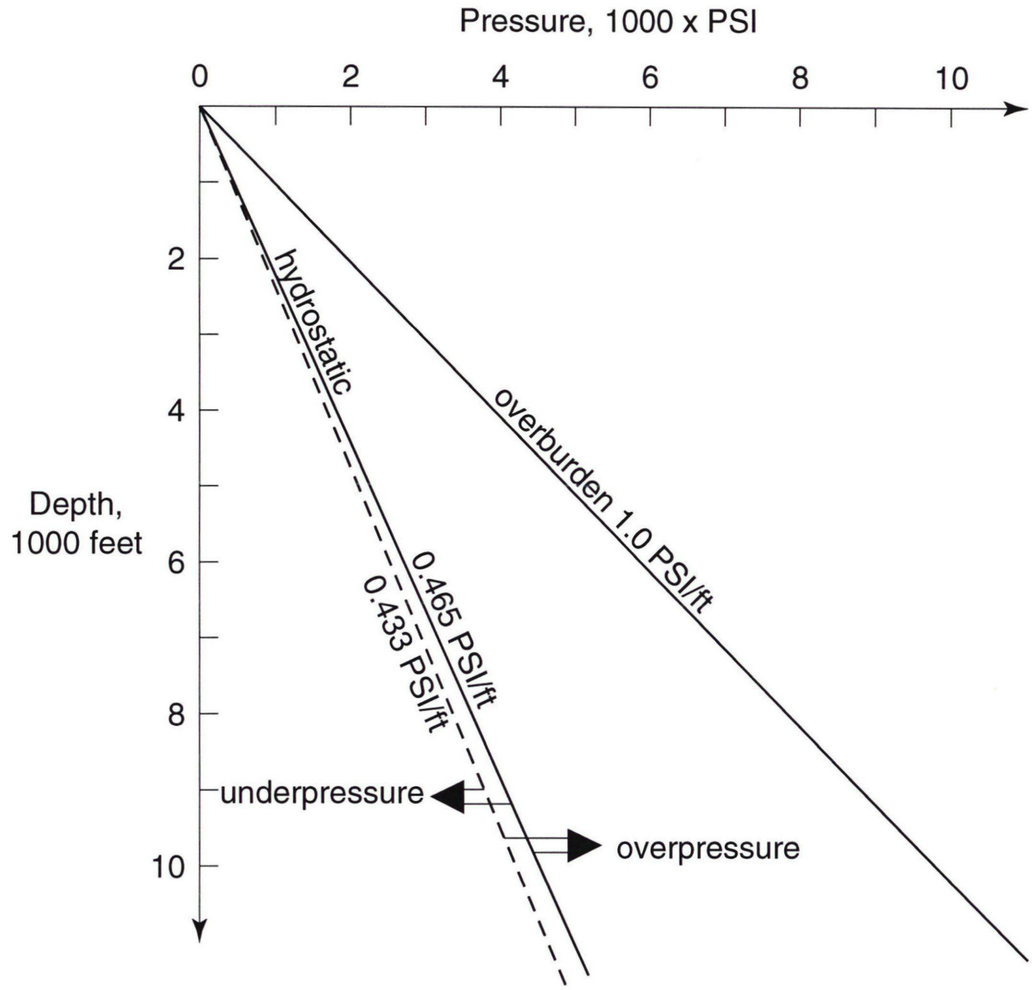



Fig. 2. Schematic diagram of subsurface formation-pressure environment concepts (after Fertl & Chilingarian, 1977).

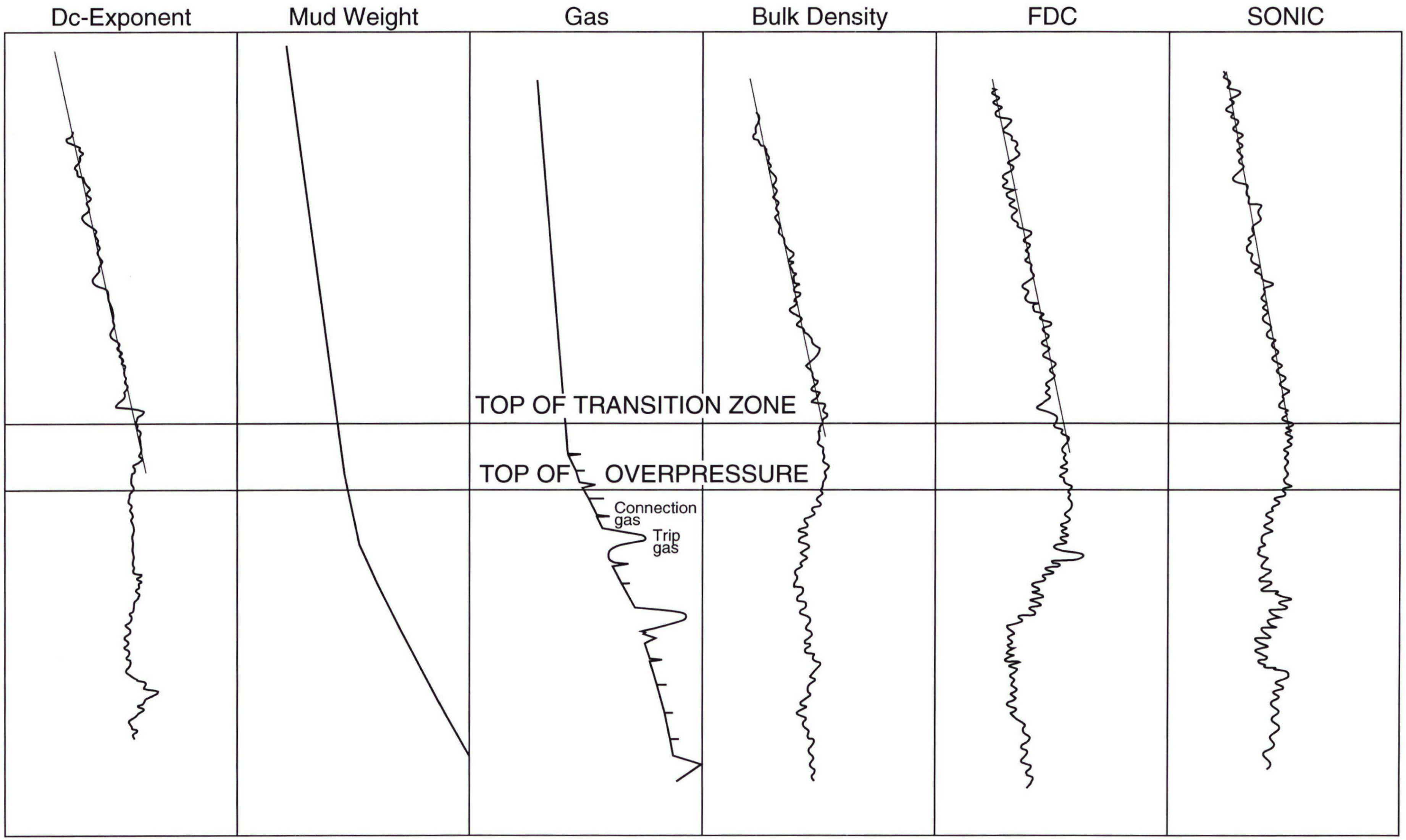



Fig. 3. Diagram to show schematic response of drilling and geological indicators in zones of overpressure.

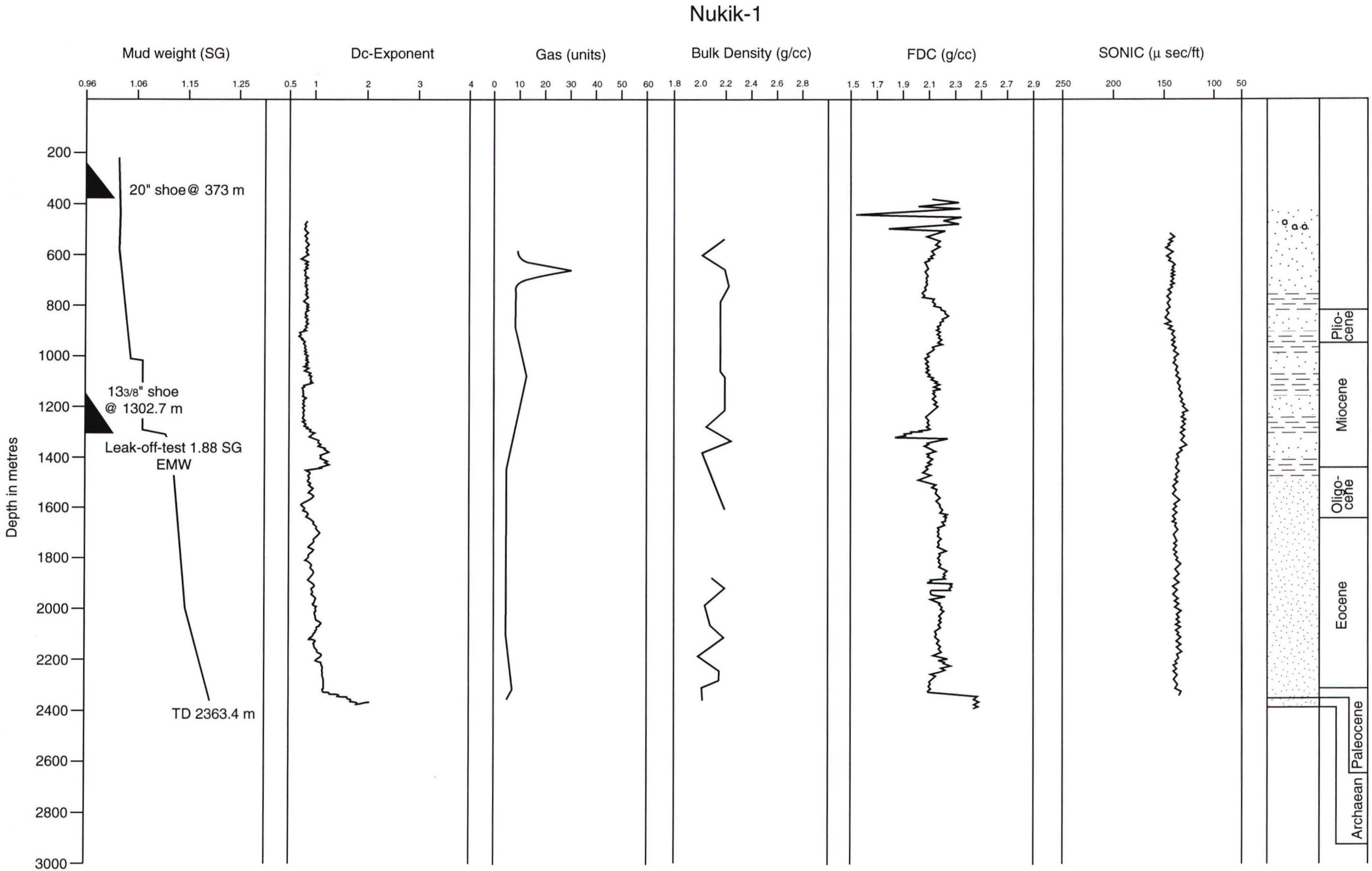



Fig. 4. Pressure indicators for well Nukik-1.

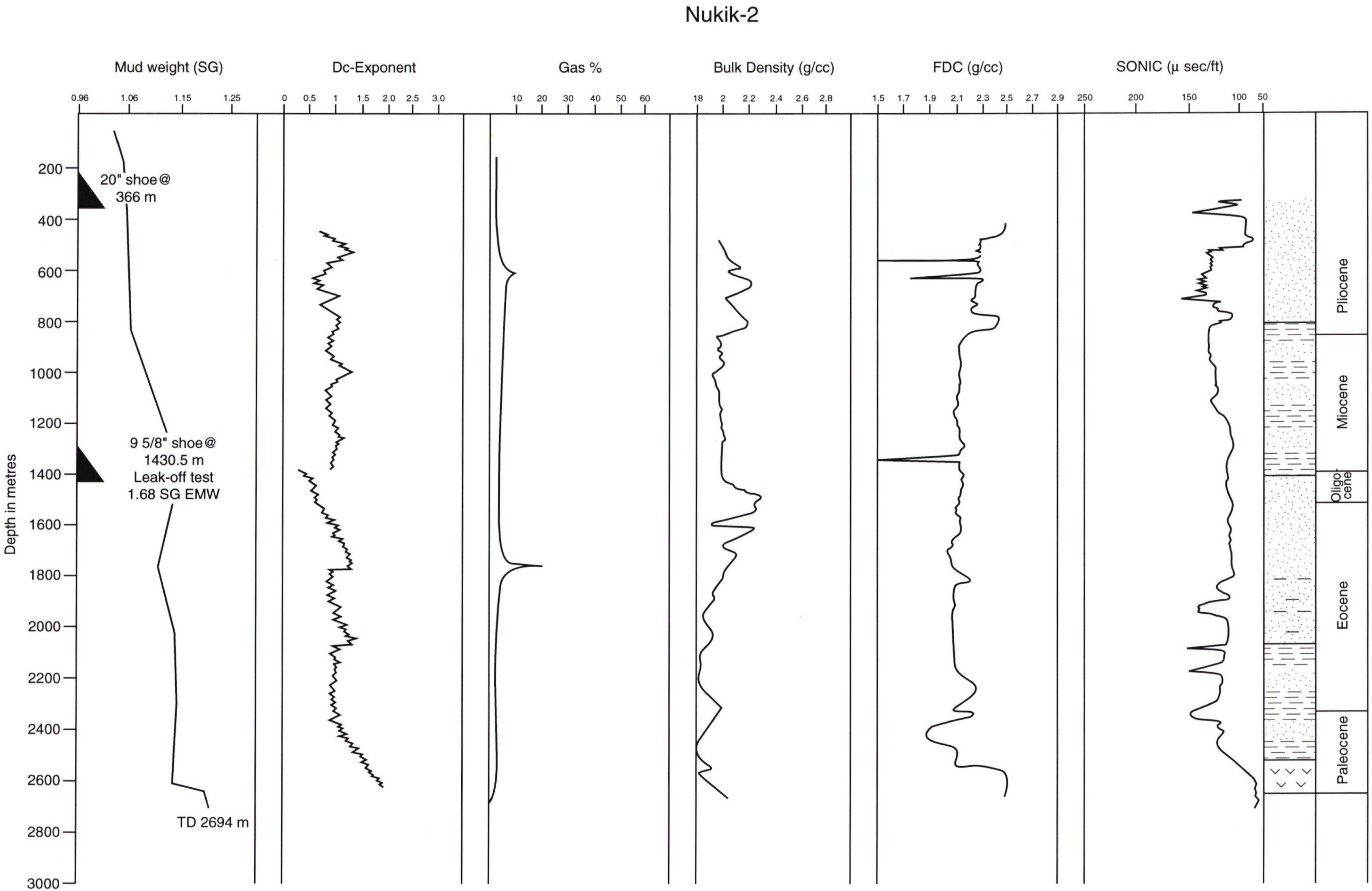



Fig. 5. Pressure indicators for well Nukik-2.

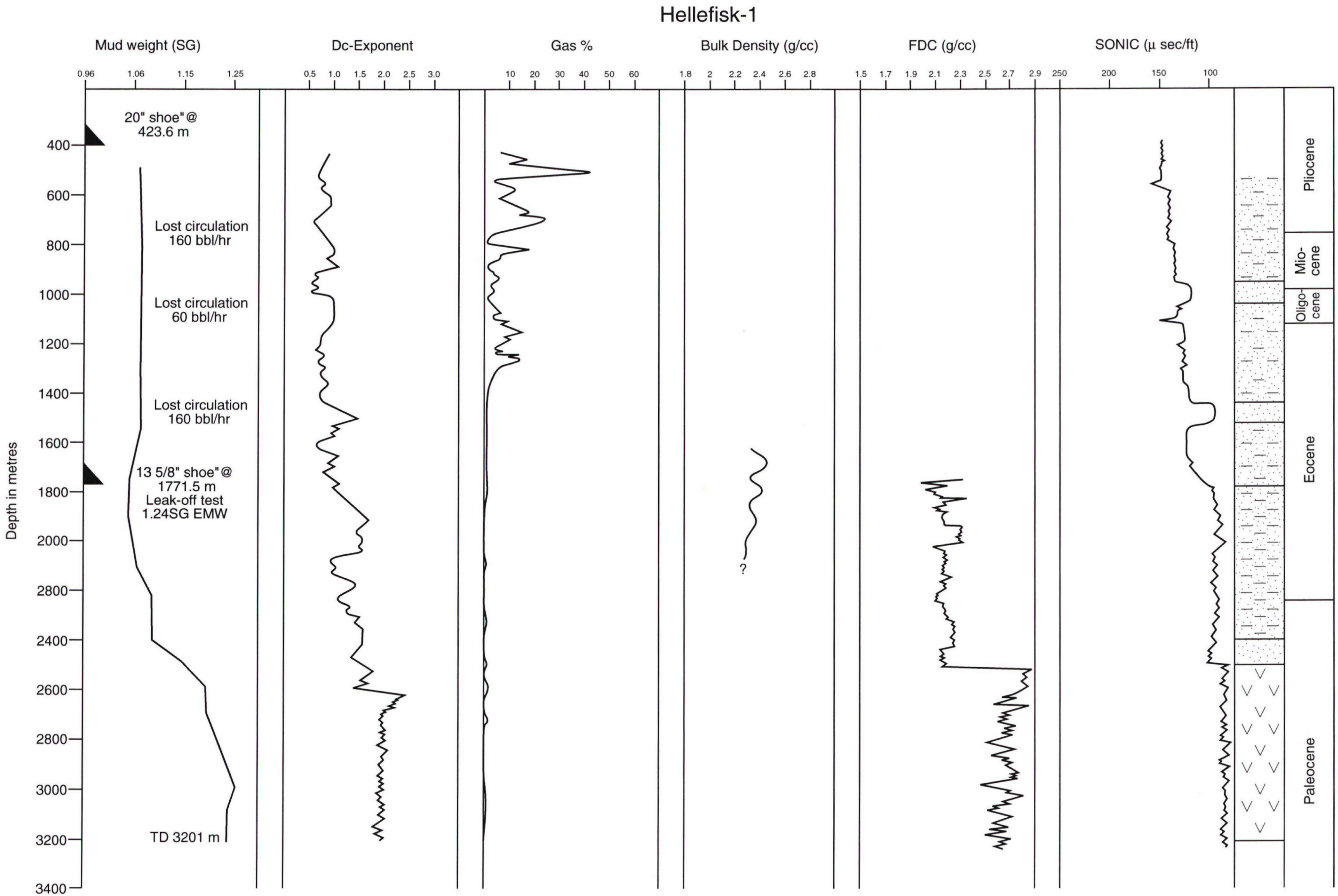



Fig. 6. Pressure indicators for well Hellefisk-1.

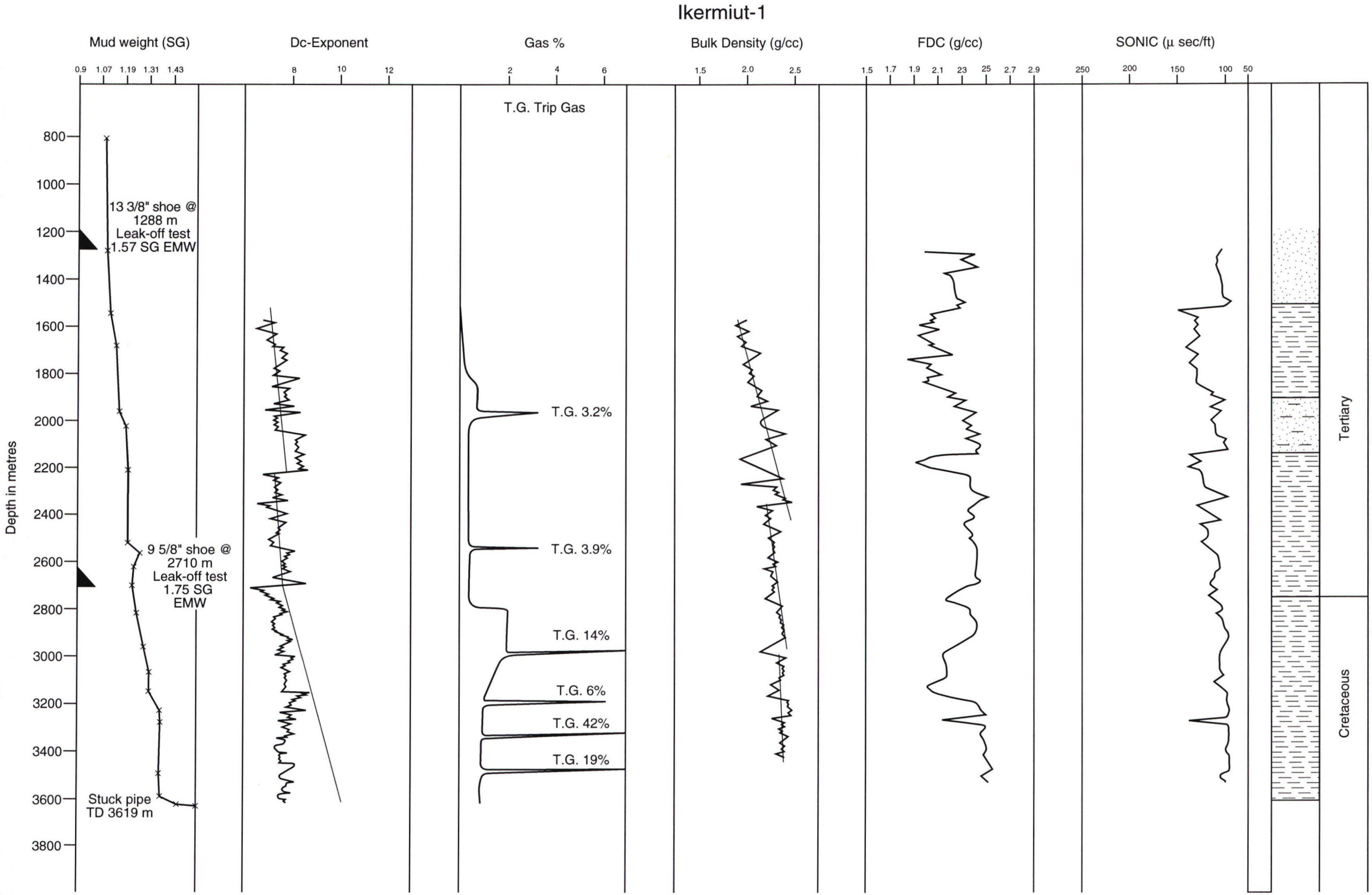



Fig. 7. Pressure indicators for well Ikermiut-1.

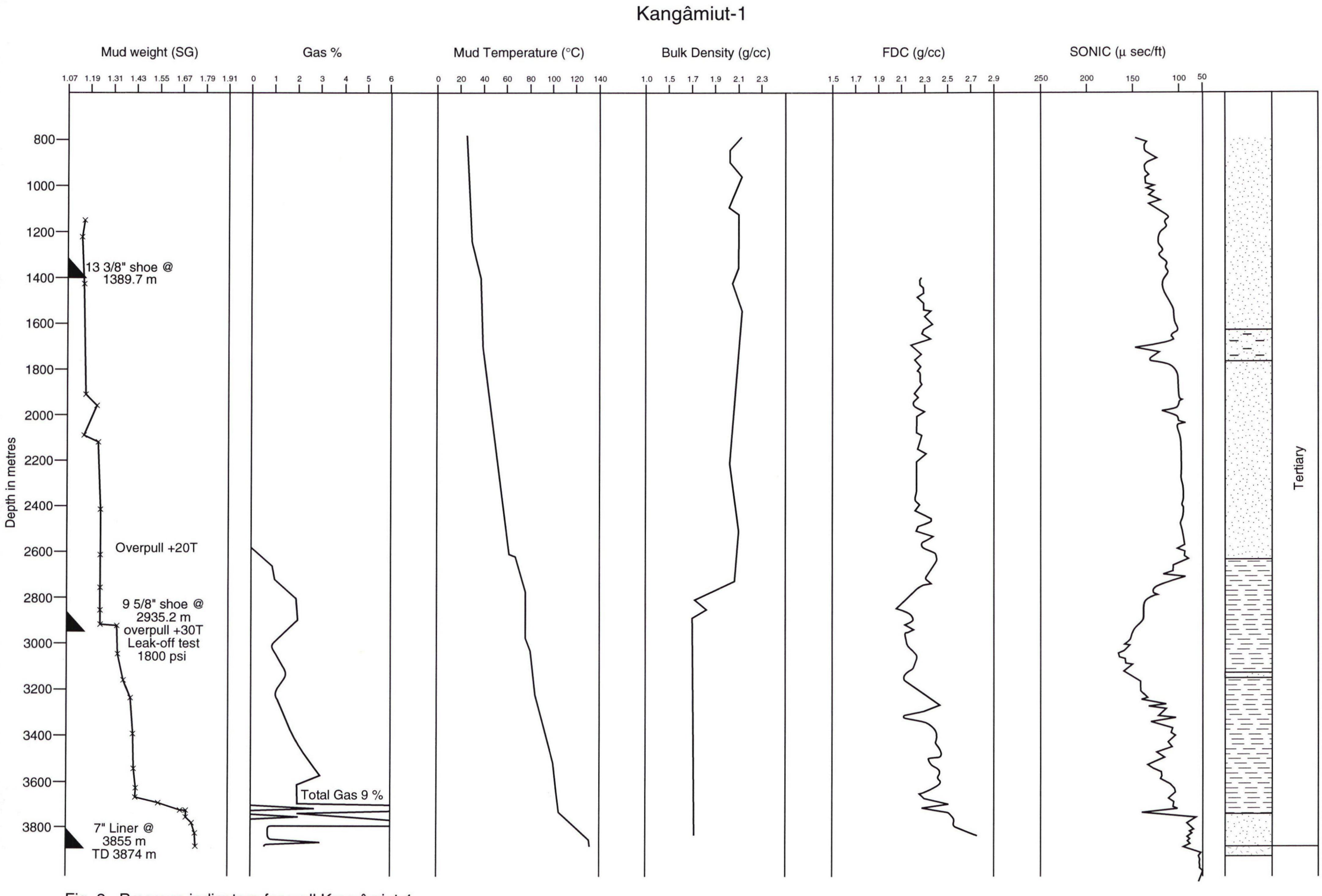



Fig. 8. Pressure indicators for well Kangâmiut-1.

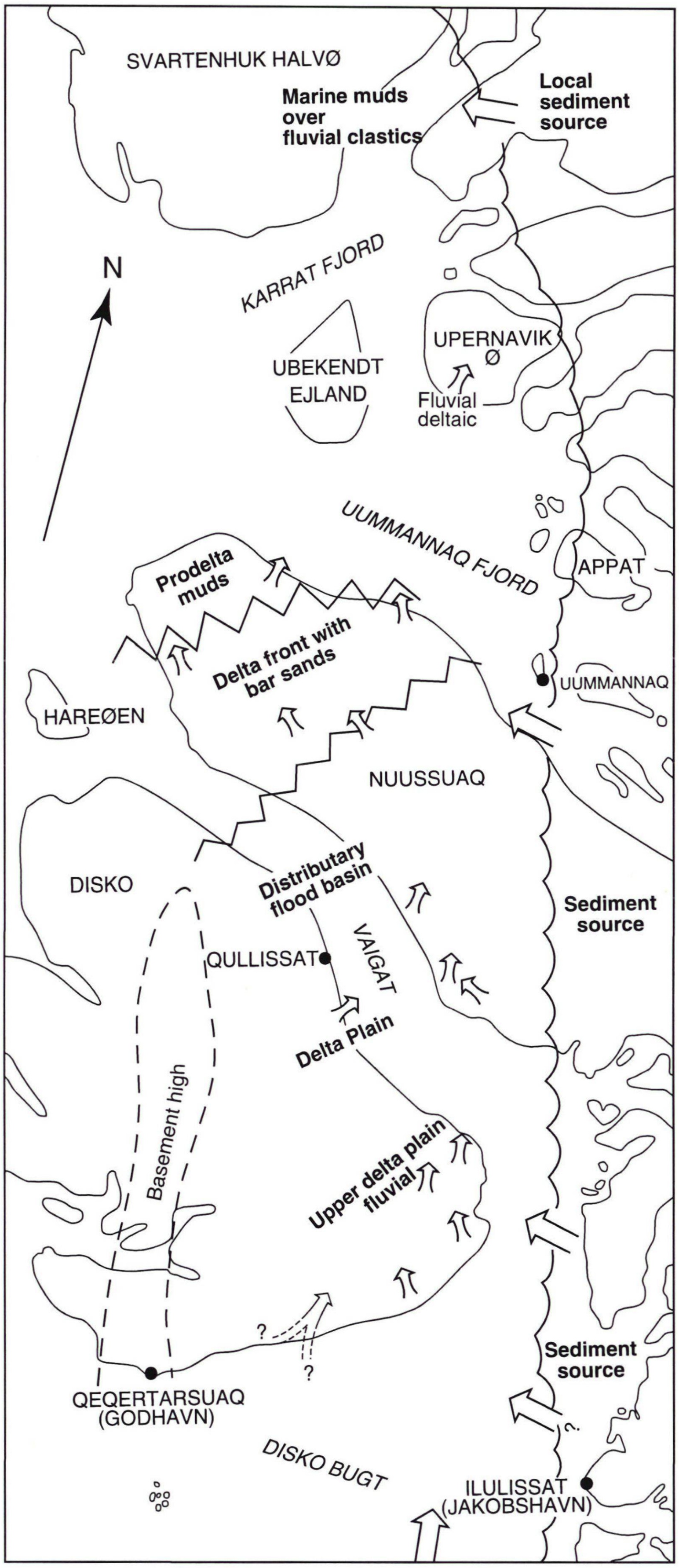
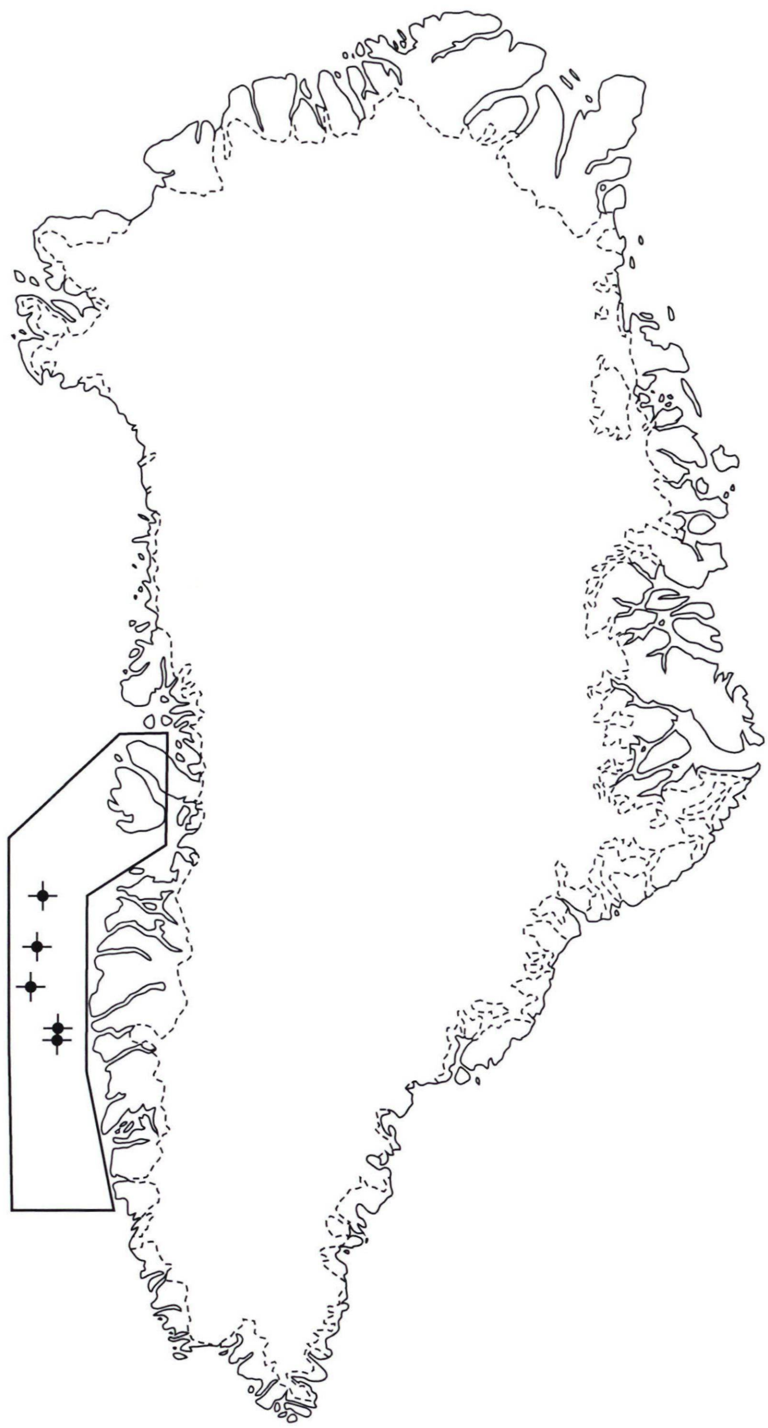



Fig. 9. Generalised facies distribution with sediment transport direction for the Cretaceous rocks of central West Greenland (after Henderson et al., 1976).



ISSN 0903-7322