2

THE LOGGING ENVIRONMENT

2.1 Introduction

Treated simply as an instrument of measurement, a logging tool is required to do two things: to give a true, repeatable reading, and to make the reading of a representative, undisturbed sample of the subsurface formation. For the following reasons, neither of these ideals can be realized.

The first is that the undisturbed formation environment is irrevocably disturbed by drilling a well. The new drill-created conditions are those in which the logging tools work. A tool can only 'guess' at the original states. This chapter examines what is involved in this guess, in terms of drilling pressure, drilling temperature and invasion.

The second reason is that the ideal conditions for a perfect geophysical measurement cannot be met in borehole logging methods. Ideal conditions would require a logging tool to be motionless for each individual measurement, and to have a sensor of zero dimensions measuring a point sample. Sensors have dimensions and tools move. Tool design acknowledges this, and a compromise is made between a practical and practicable measurement and one that is perfect. This chapter will also examine, in general terms, the effects of the logging method on the measurements made. The notions of depths of investigation, minimum bed resolution and bed-boundary definition will be discussed.

2.2 The pressure environments of borehole logging and invasion

The pressure environment during drilling and, inevitably, during logging, is made up of an interplay between two elements; formation pressure and drilling-mud column pressure.

The formation pressure is the pressure under which the subsurface formation fluids, and gases are confined. The pressure of the drilling mud is hydrostatic and depends only on the depth of a well, that is the height of the mud column, and the mud density. Maintaining the pressure exerted by the column of drilling mud at just a little above the pressure of the subsurface formations encountered is one of the necessities for equilibrium drilling: it is a delicate balance. The two pressure environments are examined below.

Hydrostatic pressure

Fluids transmit pressure perfectly so that the pressure exerted by the column of fluid is dependent simply on the height of the fluid column and the density of the fluid. The pressure in kg in a column of water can be calculated thus:

$$\frac{\text{height of water column (m)} \times \text{density (g / cm}^3\text{)}}{10} = \text{pressure (kg) per sq. cm} \qquad (1)$$

For a column of pure water of 2500 m (density of pure water = 1.00 g/cm^3)

$$\frac{2500 \times 1}{10} = 250\,\text{kg / cm}^2 \qquad (2)$$

In oilfield terms, the pressure of a column of fluid may be expressed by its pressure gradient. Thus pure water has a gradient of 1.00 g/cm^3. That is, a column of pure water will show a pressure increase of 1 kg/cm^2 per 10 m of column (or 1 g/cm^2 per cm of column) (Figure 2.1). The term 'column of water' is used as applicable to wells: 'depth' is equally applicable and more understandable when talking about water masses, such as the oceans.

As water becomes more saline, its density increases (Figure 2.2). Water which has a salinity of 140,000 ppm (parts per million) of solids (mainly NaCl), has a density

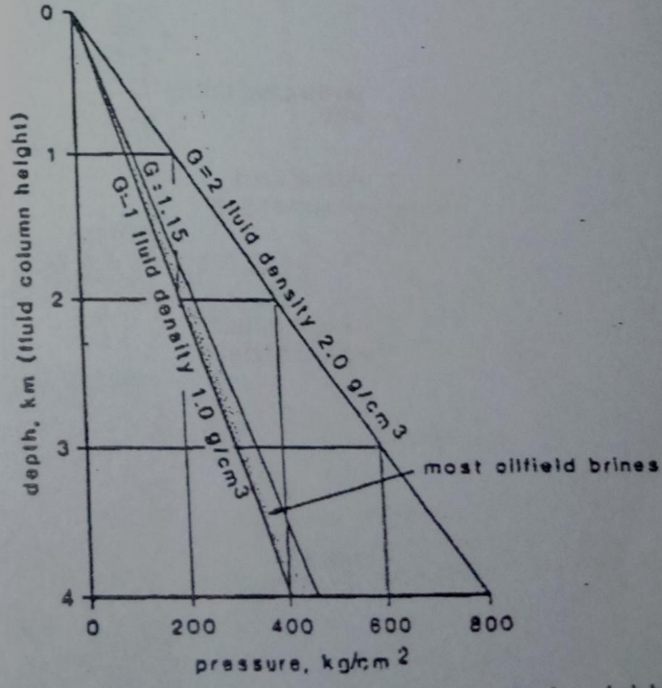

Figure 2.1 Fluid pressure gradients related to depth, or height of fluid column.

Fluvial System

Khalid.

4

CALIPER LOGS

Caliper tools measure hole size and shape. The simple mechanical caliper measures a vertical profile of hole diameter (Figure 4.1). The more sophisticated borehole geometry tools record two simultaneous calipers and give an accurate borehole shape and orientation.

4.1 Mechanical calipers – the tools

The mechanical caliper measures variations in borehole diameter with depth. The measurements are made by two articulated arms pushed against the borehole wall. The arms are linked to the cursor of a variable resistance (Figure 4.2). Lateral movement of the arms is translated into movements of the cursor along the resistance, and hence variations in electrical output. The variations in output are translated into diameter variations after a simple calibration. Frequently logging tools are automatically equipped with a caliper, such as the micrologs (Chapter 6) and the density-neutron tools (Chapters 9, 10) where the caliper arm is used to apply the measuring head of the tool to the borehole wall. Sophisticated, dual caliper tools, such as the Borehole Geometry Tool of Schlumberger, also exist specifically for measuring hole size and volume. However, today, such information is generally taken from dipmeter tools, which acquire geometry data in order to derive dip (Chapter 12). These tools have four pads fixed at right angles, opposite pairs being linked but independent of the perpendicular set. This, in terms of geometry, gives two independent calipers at 90°. The tool also contains gyroscopic orientation equipment so that the azimuth (bearing) of the two calipers is permanently defined.

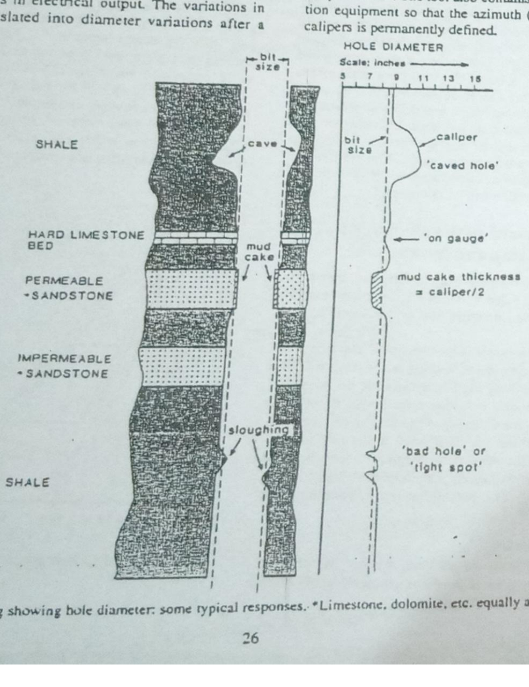

Figure 4.1 The caliper log showing hole diameter: some typical responses. *Limestone, dolomite, etc. equally applicable.

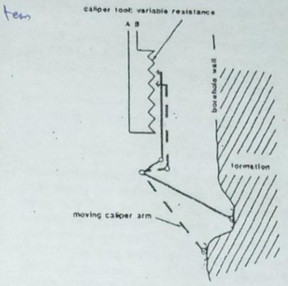

Figure 4.2 Schematic caliper tool showing the conversion of a mechanical movement to an electrical signal using a variable resistance. (Adapted from Serra, 1979).

4.2. Log presentations

The caliper log is printed out simply as a continuous value of hole diameter with depth (Figure 4.3). The curve is traditionally a dashed line and usually plotted in track 1. The horizontal scale may be inches of diameter or, in the differential caliper, expressed as increase or decrease in hole diameter about a zero defined by the bit size (Figure 4.3). The ordinary caliper log is accompanied by a reference line indicating bit size.

The geometrical data from four-arm, dual-caliper tools such as the dipmeter are presented in various formats, only one of which is shown (Figure 4.4). The two hole diameters measured by the two calipers are combined with the directional elements of tool orientation (pad 1 azimuth), hole deviation and azimuth of the deviation. An integrated hole volume may be added as horizontal ticks on the depth column giving a continuous record of hole volume (not on the example).

The calipers of the example presented (Figure 4.4), show the geometry tool turning slowly as it moves upwards in a persistently oval hole with a small diameter of approximately 9" and a large diameter of approximately 11". The larger diameter is oriented nearly north to south as indicated by the pad 1 azimuth over the depth 0–15 m (calipers 1–3 in larger diameter). At depth 30 m, calipers 2–4 show the larger radius (approx. 11"), calipers 1–3 the smaller (approx. 9"). The rotation of the tool is indicated by the persistent change in the pad 1 azimuth and explains the caliper cross-over at depth 17 m (where both calipers show the same diameter but the hole is still oval). Above this, calipers 1–3 follow the larger diameter (approx. 11"), while calipers 2–4 follow the smaller (approx. 9").

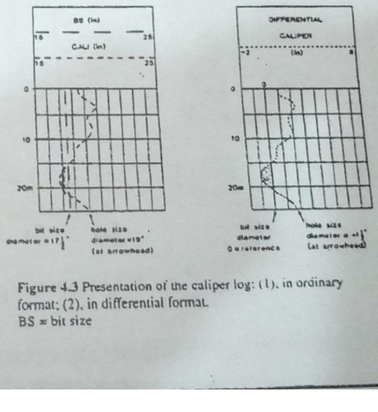

Figure 4.3 Presentation of the caliper log: (1), in ordinary format; (2), in differential format.
BS = bit size

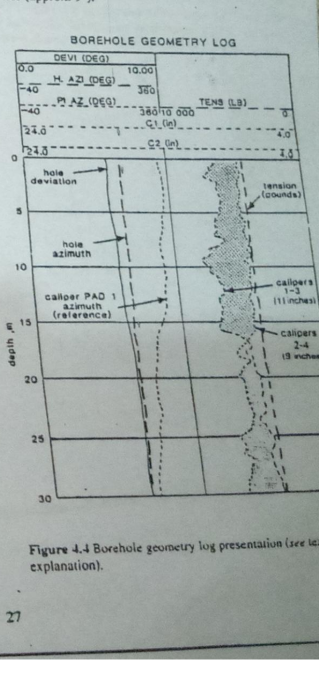

Figure 4.4 Borehole geometry log presentation (*see te*
explanation).

4.3 Simple, two-arm, caliper interpretation

Increase in borehole diameter

The simple caliper log records the mechanical response of formations to drilling. A hole that has the same size (diameter) as the bit which drilled it, is called *on gauge* (Figure 4.1). On gauge holes are the target for all drilling and essentially indicate good drilling technique. Holes with a much larger diameter than the bit size are '*caved*' or '*washed out*'. That is, during deepening of the hole, the borehole walls cave in, are broken by the turning drill pipe, or are eroded away by the circulating borehole mud. This is typical of shales, especially when geologically young and unconsolidated, so that caving can have a general lithological significance (Figure 4.1).

However, caving is also typical of certain specific lithologies such as coals or even organic shales. In some fields, even with varied drilling fluids and drilling techniques, it is found that certain stratigraphic levels habitually cave – generally for mechanical (textural) reasons. The example (Figure 4.5) shows a section of Carboniferous shale from the UK East Midlands in which moderate caving occurs in the same organic rich interval, over a wide area. The shale is either very laminated or locally fractured.

Decrease in borehole diameter

Calipers may show a hole diameter smaller than the bit size (diameter). If the log has a smooth profile, a mud-cake build-up is indicated (Figure 4.6*a*). This is an extremely useful indicator of permeability: only permeable beds allow mud cake to form. The limits of mud-cake indicate clearly the limits of the potential reservoir. Mud cake thickness can be estimated from the caliper by dividing the decrease in hole size by two (the caliper giving the hole diameter), i.e.

$$\frac{\text{bit size (diam)} - \text{caliper reading (diam)}}{2} = \text{mud cake thickness}$$

It should be remembered that this thickness may vary between tools. The caliper of a density tool is applied harder to the formation than the caliper of a micro-log: the former probably causes a groove in the mud cake and therefore gives a thinner, log derived mud-cake thickness.

Boreholes with a smaller diameter than the bit size but rugose, are probably sloughed (Figure 4.6*b*). The zones of small holes will be the 'tight spots' encountered during drilling, trips or logging. That is, it will be at these points that tools stick or the bit gets stuck while being pulled out of the hole. A frequent cause of tight spots is abundant smectite in the clay mineral mixture. Smectite is a swelling clay which takes water from the drilling mud, expands, breaks from the formation and sloughs or collapses into the hole. The Gulf Coast 'gumbo', which often causes hole problems, is smectite rich.

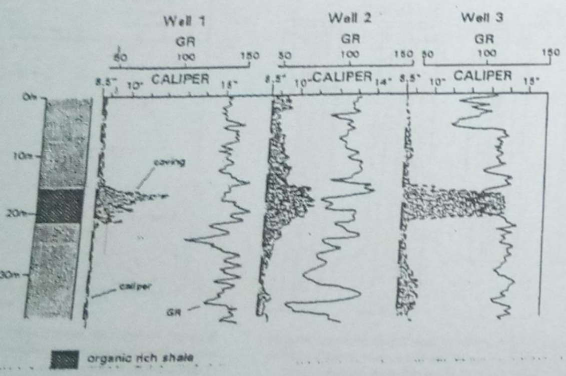

Figure 4.5 Consistent caving, indicated on the caliper log, over the same, organic rich, stratigraphic level in three different wells. Upper Carboniferous, East Midlands, U.K.

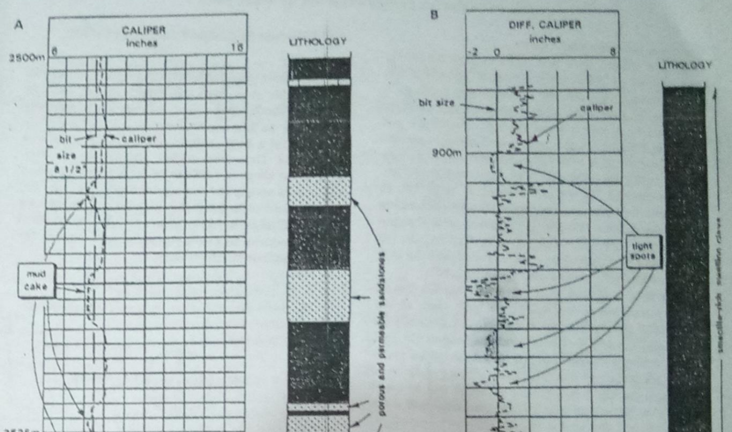

Figure 4.6 Hole size diminution seen on the simple caliper. (A) Mud-cake build-up opposite porous and permeable sandstones. (B) Tight spots in a shale sequence caused by hole sloughing due to swelling clays.

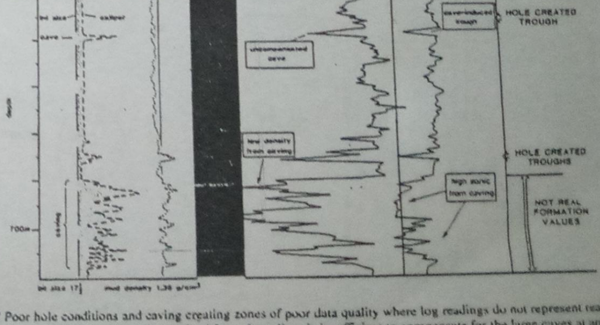

Figure 4.7 Poor hole conditions and caving creating zones of poor data quality where log readings do not represent real formation values. The automatic density correction derived from the caliper is insufficient to compensate for the large caves at around 700m. The density and sonic logs suggest a formation change at 690m, but the interval is homogeneous from top to bottom, being poorly consolidated clay/shales.

Quality control using the caliper

With the simple, two arm caliper, one extremely important use is in the quality control of logs in general. When caving is serious, the quality of log readings is impaired. In some tools, such as the micrologs, a caliper is registered simply because the tool sensors are pad mounted. Lack of pad contact with the formation, a problem in rugose holes with pad-mounted tools, is quickly seen by using the caliper. In other tools, such as the formation density, the caliper reading is used for an automatic hole size and mud-cake thickness correction or compensation (Chapter 9). Caving will demand inordinately large corrections to many logs and the log values will be of little use. It is therefore essential to look at the caliper before using any logs (Figure 4.7).

However, it should be pointed out that the simple caliper attached to the open hole tools such as the micrologs and the formation density, will generally be pessimistic in terms of hole condition, because in oval holes a simple caliper will naturally open to the maximum diameter of the borehole (Figure 4.8). And although the log measurements recorded will be made across the larger diameter, the hole condition itself is not as bad as may first appear.

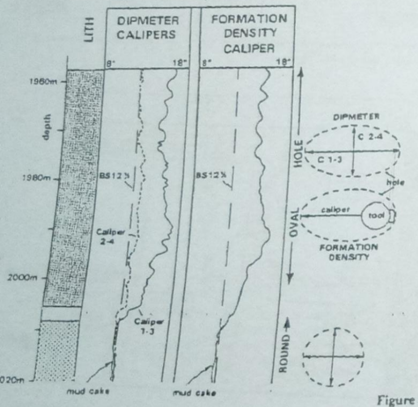

Figure 4.8 Comparison between the simple caliper of the ormation density tool and the two-arm caliper of the lipmeter tool in an oval hole. The simple caliper normally xtends to the long axis in an oval hole.

4.4 Four-arm caliper interpretation

Breakouts

A great deal more information can be gained from dual caliper tools than from the simple caliper tool. As indicated above, dual caliper information is generally taken from the four-arm dipmeter tool.

Using just a single caliper, borehole shape cannot be interpreted. Data from a four arm caliper however, enables the shape of a hole to be much better defined. A hole can be seen to be 'on gauge' and round (Figure 4.9*a*) or oval and 'washed out' (Figure 4.9*c*) or enlarged by a 'key seat' (Figure 4.9*b*): When oval, the direction of enlargement can be given. However, much more can be interpreted from borehole shape.

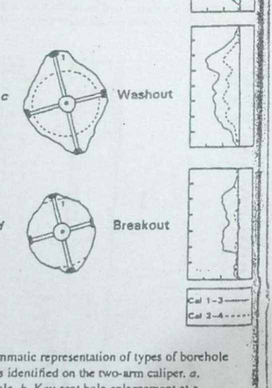

Figure 4.9 Diagrammatic representation of types of borehole shape and profile as identified on the two-arm caliper. *a*. Round, in-gauge hole. *b*. Key seat hole enlargement at a dogleg. *c*. Washout hole enlargement due to general drilling wear. *d*. Breakout, showing characteristic oval hole with abrupt vertical limits (re-drawn, modified from Plumb and Hickman, 1985).

Three main types of elliptical borehole have been recognized, 'keyseats', 'washouts' and 'breakouts' (Figure 4.9). Washouts develop from general drilling wear, especially in shaly zones and dipping beds. On the geometry logs, a washout has a considerable vertical extent and both calipers are larger than the drill bit size with one caliper being much larger than the other. Shape changes are variable and gradual (Figures 4.9*c*; 4.10.2). Keyseats are asymmetric oval holes, formed by wear against the drill string at points where the borehole inclination changes (doglegs) (Figure 4.9*b*). Both washouts and keyseats are general drilling phenomena: breakouts, however, have a specific cause.

Breakouts are recognised using the following strict criteria (Figure 4.11) (i.e. Bell, 1990):

1. The tool must stop rotating (ideally the tool should rotate before and after a breakout zone).
2. The calipers must separate to indicate an oval hole. The larger caliper should exceed hole gauge: the smaller caliper should not be less than hole gauge and its trace should be straight (the caliper difference should be larger than 6 mm and the zone of elongation greater than 1.5 m). The limits of the breakout should normally be well marked.
3. The larger diameter of hole elongation and its direction should not consistently coincide with the azimuth of hole deviation.

Breakouts are considered to form as a the result of the interaction of stresses induced by drilling and the existing stress regime of the country rock (Bell and Gough, 1979). Small brittle fractures (spalling) occur in the borehole around a rotating bit which, if there is unequal horizontal stress in the formation, form in a preferential direction, that of the minimum horizontal stress, Sh_{min} (Figure 4.12, *a*). In more precise terms, compressive shear fracturing of the borehole wall is localised in the direction of the minimum horizontal formation stress Sh_{min}, and is the cause of breakouts (Bell, 1990). Laboratory experiments and empirical observations seem to back up the theory (*see* Prensky, 1992b for a review and references). Hence, breakouts indicate the present day stress-field orientation and are independent of lithology, dip and existing fractures or joints.

Breakout studies to define in-situ stress fields are now being carried out on many scales from the local to the global. On the global scale, breakout derived stress-field orientations are similar to those derived from earthquake studies and tend to indicate intra-plate tectonic stresses (Zoback *et al.*, 1989). On a local scale, breakout studies have an importance for field development (Figure 4.13). Natural and artificial fractures are most likely to be oriented in the maximum horizontal stress direction Sh_{max} (i.e. normal to breakouts) (Figure 4.12.*b*). Fracture connection between wells during field production is then more likely in this orientation (Bell, 1990). It is also possible that horizontal drilling will be more stable in the Sh_{max} (maximum horizontal stress) direction (Hillis and Williams, 1992).

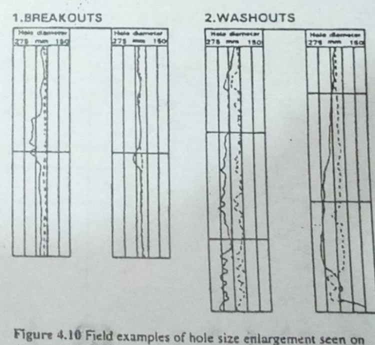

Figure 4.10 Field examples of hole size enlargement seen on the two-arm, dual caliper. 1. Breakouts, seen as well-defined, oval hole developments. 2. Washouts, seen as generalised hole ovality. Hole diameter increases to the left (from Cox, 1983).

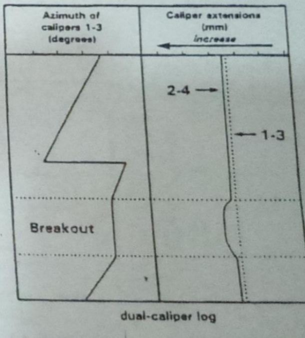

Figure 4.11 Schematic representation of the characteristics used to identify breakouts on caliper logs (re-drawn from Yassir and Dusseault, 1992).

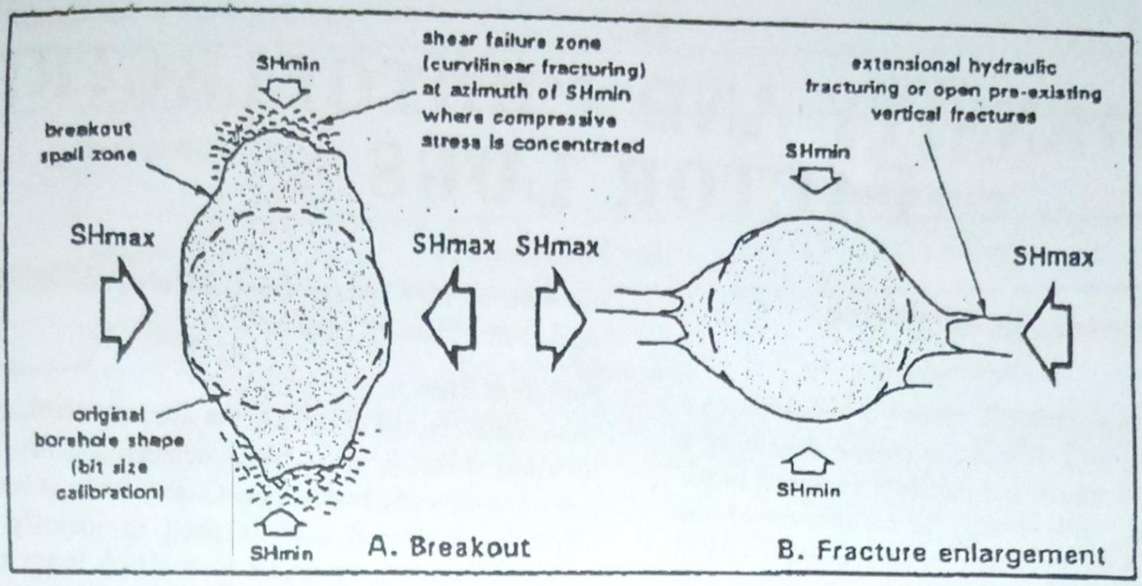

Figure 4.12 Horizontal stress field relationship to borehole shape. a. Breakout formation due to spalling during drilling, in the direction of minimum horizontal stress (Sh_{min}). *b*. Hole enlargement along drilling induced extensional fractures oriented in the direction of maximum horizontal stress (Sh_{max}) (modified from Dart and Zoback, 1989 and Hillis and Williams, 1992).

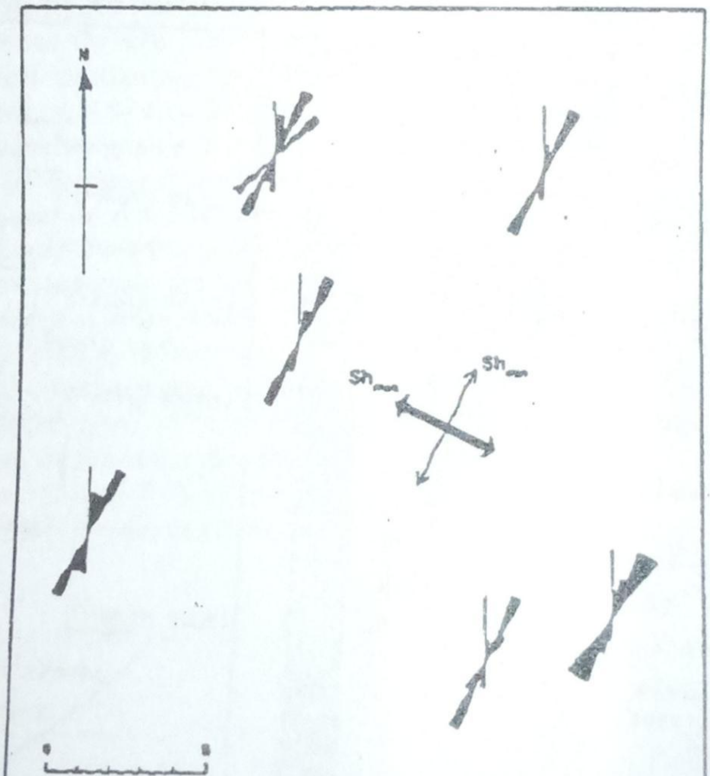

Figure 4.13 Consistently oriented breakouts, identified from dipmeter caliper data in an offshore field, indicating the present day, horizontal stress field. Depth of analysed interval from 2.5 to 3.5 kilometres. Sh_{min} = minimum horizontal stress, Sh_{max} = maximum horizontal stress.