HOLE STABILITY THROUGH MUD TECHNOLOGY AN ORGANIZED APPROACH

NORMAN K. TSCHIRLEY
Baroid Division, N L Industries, Inc.

INTRODUCTION

This paper is intended to have a twofold purpose. While the data cited refer to the specific problem of borehole instability as affected by the drilling fluid, it is also intended that the approach taken toward alleviation of the borehole instability problem through mud technology in this case is applicable to other drilling problems as well. Borehole instability serves as an example of a drilling problem to illustrate how drilling problems may be approached in an organized manner by way of the drilling mud.

The varied drilling problems that are susceptible to alleviation in part through the drilling fluid, may be approached systematically by considering the drilling problem in terms of the fundamental characteristics of drilling fluids. These fundamental characteristics are stated in Fig. 1. More detail could be added to the criteria listed. Solids content could be listed in addition to weight, for example. Nevertheless, if a given drilling problem is considered carefully in terms of the criteria listed, it will be found that the analysis thus carried out will be accurate and reasonably thorough, insofar as the problem in question is subject to solution through the drilling fluid. Futhermore, in addition to serving as a guide for the application of mud technology, these same criteria point to areas in which improvements in presently existing technology may be sought.

In the text to follow, the problem of borehole instability will be analyzed in terms of the weight, rheology, filtrate and other characteristics of the drilling fluid.

Of the various rocks that are penetrated in the course of drilling a well, the rock most likely to be unstable is shale. Both sandstones and carbonate rocks may be unstable when subjected to tectonic stresses or when the hydrostatic mud pressure is lower than the pressure on the fluids in the rocks, particularly when the permeability is low. But the instability problem with shale is compounded by the extraordinary manner in which this rock is affected by wetting with water.

FUNDAMENTAL CHARACTERISTICS of DRILLING FLUIDS

1. WEIGHT

2. RHEOLOGY
- Plastic Viscosity
- Yield Point
- Gel Strength
- Sec/Qt

3. FILTRATE
- Quantity
- Quality

4. OTHER
- Lubricity
- Corrosivity
- Osmotic Effects

FIGURE 1

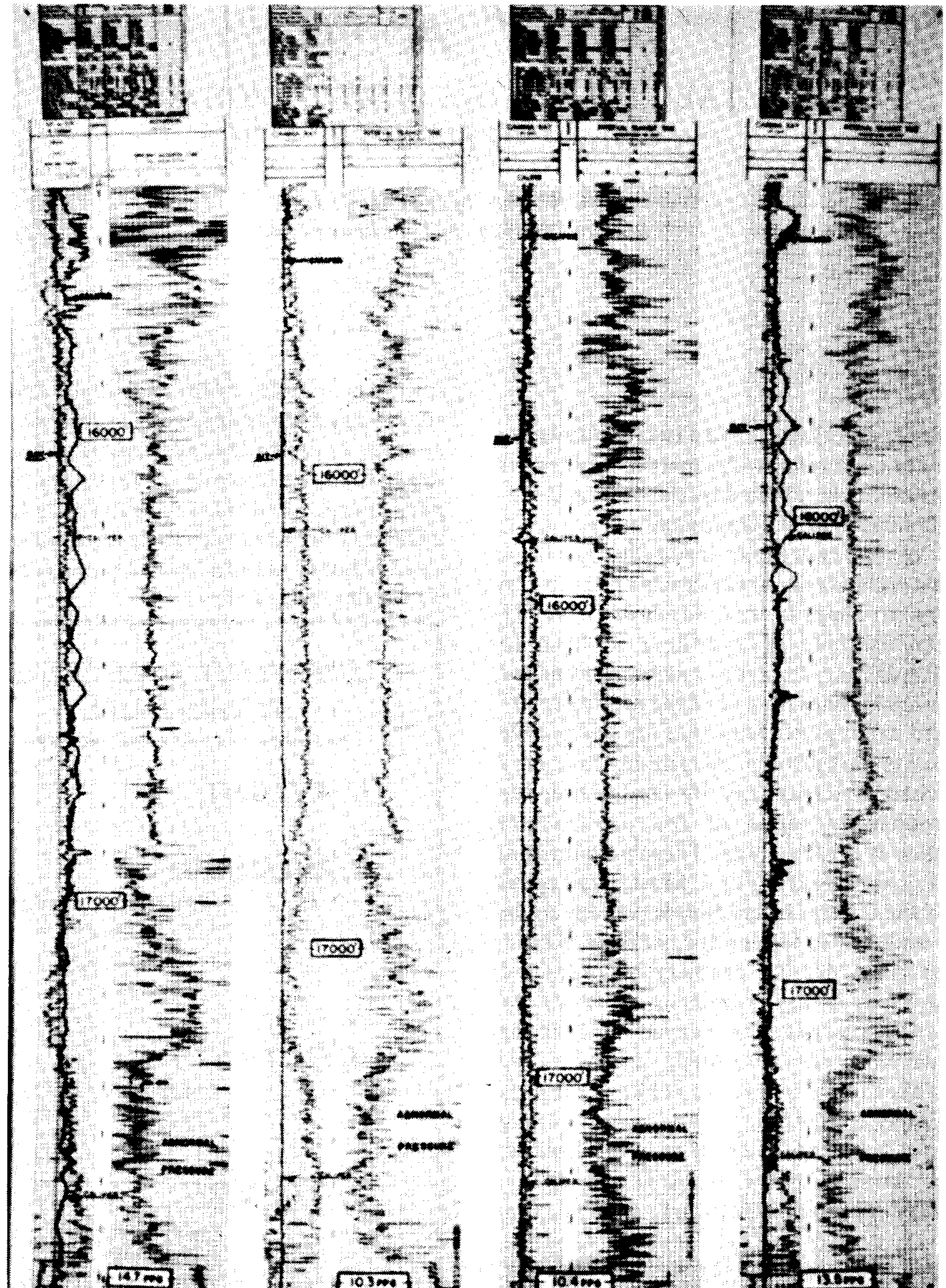

FIG. 2 — HOLE STABILITY VERSUS MUD WEIGHT, PORE PRESSURE AND MUD TYPE, DELAWARE BASIN.

RELATIONSHIP BETWEEN HOLE STABILITY AND MUD WEIGHT

Hole stability as affected by mud weight would be expected to depend upon the formation pore pressure. Mud weight sufficient to counterbalance pore pressure should provide stability insofar as stability may be obtained through mud weight. Maintenance of hole stability at underbalance would depend upon the strength characteristics of the rock matrix, the fluid in the rocks, the drilling fluid, and finally upon the effect of the drilling fluid upon the rock. Many shales can be drilled at some degree of underbalance with little sacrifice in hole stability. The degree of underbalance that may be tolerated in a given shale depends largely upon the sensitivity of the shale to water-wetting, and on the capability of the drilling fluid to minimize or prevent water-wetting of the shale.

Drilling at underbalance is done routinely in parts of the Delaware Basin of West Texas, where it has been found by experience that this procedure is feasible.[1] Borehole stability at varied degrees of underbalance as affected by mud type is suggested in Fig. 2. Well depths in the sonic and gamma ray logs shown include the interval from the Wolfcamp through the Pennsylvanian that is usually abnormally pressured. Maximum pressures are indicated with good accuracy by the sonic log[2] and may be assumed to range between the mud weight equivalents of 16-18 ppg in the examples shown. The estimated degree of underbalance corresponding to mud type is tabulated below, using the conservative 16 ppg as actual formation pressure.

	Ppg. max	Depth, ft	Under-balance, psi
Fresh-water (disp) Mud	14.7	17,400	1180
Oil Mud	10.3	17,400	5160
Oil Mud	10.4	17,100	4980
Fresh-water (non-disp) Mud	13.5	17,300	2250

Looking now at the caliper, Fig. 2, the following observations are considered pertinent in the context of hole stability versus mud weight:

1. Fresh-water nondispersed mud provided a more stable hole than fresh-water dispersed mud, even at a greater degree of underbalance.
2. Salinity-controlled oil mud at roughly 5000 psi underbalance provided a more stable hole than either of the two water-base muds at a much lesser degree of underbalance.

Pore Pressure Estimates

In the examples of Delaware Basin wells just cited, pore pressures are known with a good degree of accuracy. Sufficient permeability has been found to exist in some wells, thus permitting a pressure measurement by drill-stem testing. These pressure measurements, in turn, substantiate pressure estimates from electric logs. Figure 3[3] shows an example of an electric log from which a pressure determination is more difficult to make. As the caliper and accompanying notes suggest, borehole instability was a serious problem on this well. There was no evidence of serious formation fluid intrusion during the course of the operation.

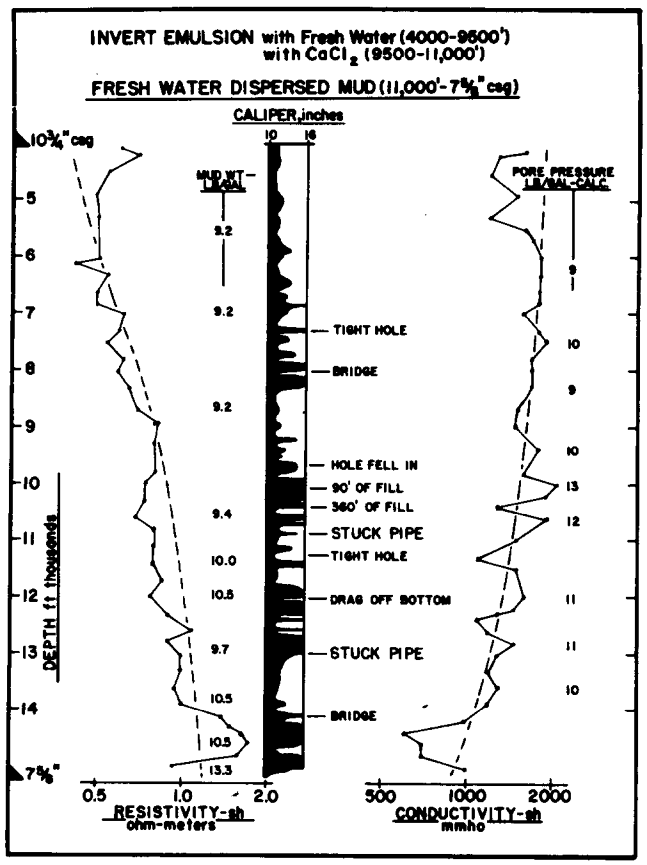

FIG. 3—HOLE STABILITY AND PORE PRESSURE ESTIMATES, OFFSHORE LOUISIANA.

Resistivity and conductivity logs are both plotted as a means of trying to estimate pore pressure and to explain the severe hole instability observed. The normal compaction line is difficult to locate for the resistivity log, and no quantitative pressure estimate is attempted from it. Pore pressures listed are calculated from the conductivity log.[4] Substantiation by drill-stem testing in shale would have had no hope of success at all. Note that estimated pore pressure exceeds mud pressure in several sections of the hole. While these pore pressure estimates may be questioned quantitatively, it may nevertheless be assumed that a pressure increase is suggested qualitatively when the resistivity curve deviates to the left and conductivity to the right. If this approach is taken, the evidence thus obtained suggests that borehole instability may indeed have been attributable to a condition of pressure underbalance in this case. When the log plots indicate increasing pore pressure (e.g., at 7200; 9800; 11,800; and 12,700 ft), the hole diameter increases. That is to say, the tendency toward hole instability increases with the supposed degree of underbalance. Conversely, when the log plots indicate decreasing pore pressure and therefore decreasing degree of underbalance (e.g., at 8400; 10,600; and 12,300 ft), the hole comes more nearly to gauge. If the hole instability shown in Fig. 3 is attributed in large part to pressure underbalance, then it must be accepted that abnormally pressured shales may exist adjacent to normally pressured permeable strata. The apparent anomaly in both logs at slightly below 14,000 ft may be a limey shale.[5]

The relationship between borehole instability and mud weight, while apparently simple at first glance, becomes a subject of some complexity when pressure underbalance is involved. The degree of underbalance that can be tolerated before serious deterioration in hole condition sets in is controllable to some degree through the drilling fluid, but is influenced by loosely defined variables. The important variable of shale quality is extremely wide in scope, and the fundamental variable of pore pressure may be difficult or impossible to determine with acceptable accuracy.

RHEOLOGY

The effect of mud rheology on hole stability is properly described in terms of the flow pattern of the mud in the annulus. The concepts of plug flow, laminar flow and turbulent flow are pertinent to the problem. In general, the tendency toward hole instability from erosion would be greatest when movement of the mud at the wall of the hole is at a maximum (turbulent flow), and least when such movement is at a minimum (laminar flow).

A case of hole instability that is believed to have resulted from turbulent flow is shown in Fig. 4. Notes included in Fig. 4 are self-explanatory. Electric log plots indicate normal pressure throughout the interval. Certainly, it is logical to assume that with little movement of the mud near the wall of the hole when poorly consolidated sands are penetrated, walling-off by mud cake deposition will occur much more readily than would be the case with turbulent flow.

Mud rheology is seldom adjusted drastically for borehole instability. Deliberate adjustment in rheology to bring about a change in flow pattern in the annulus is more likely to be done to improve hole

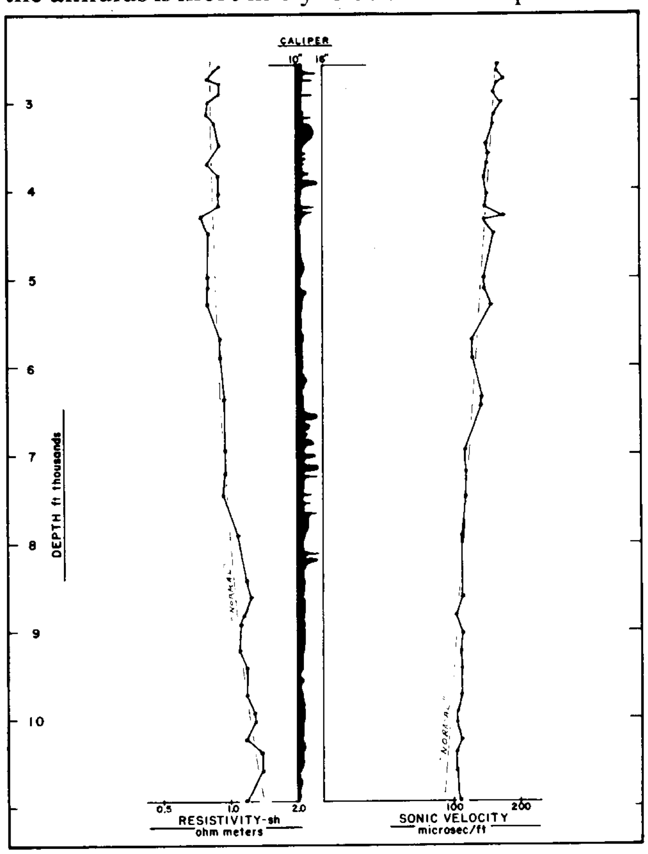

FIG. 4--HOLE EROSION IN SHALLOW SANDS, SOUTH LOUISIANA (TURBULENT FLOW OPPOSITE DRILL-COLLARS POTASSIUM BASE MUD).

cleaning or reduce back-pressure than to alleviate a borehole instability problem.

MUD FILTRATION AND HOLE STABILITY

The various tests for filtration and wall building of drilling fluids were designed to give information relative to filtrate invasion of permeable zones and to cake deposition on the faces of such zones. Empirical correlation between API filtration rate and hole stability develops in some areas; and it may be stated generally that lowering the water loss will not hurt, and may help a problem of this kind. Nevertheless, since shales are virtually all quite impermeable, the correlation between results of filtration tests and actual filtrate invasion of the shale may justifiably be held in question. It is logical to assume that filtrate invasion of shale can be restricted by constituents of the drilling fluid that have an affinity for both the shale surface and for the mud filtrate. Hydration of the various filtrate-control agents may be reflected in the measured filtration rate. The affinity of the same agents for the shale surface, however, is unlikely to be reflected in the filtration rate, and different agents may vary significantly in this regard.

Quantity of Filtrate

While it is generally accepted that the most important source of shale instability is water-wetting of the shale, there is no method available by which the rate and degree of shale-wetting can be measured in a drilling well. The complexity of the phenomenon of filtrate invasion of shale is suggested by the laboratory experiment shown in Fig. 5. The procedure by which these results were obtained are described in Reference 6.

Note that the mud with the higher API water loss allowed less filtrate to enter the shale core than the mud with the lower API filtrate. Since the higher water-loss mud contained KCl and the lower water-loss mud contained NaCl, the data suggest that the difference in filtrate invasion may be attributable to

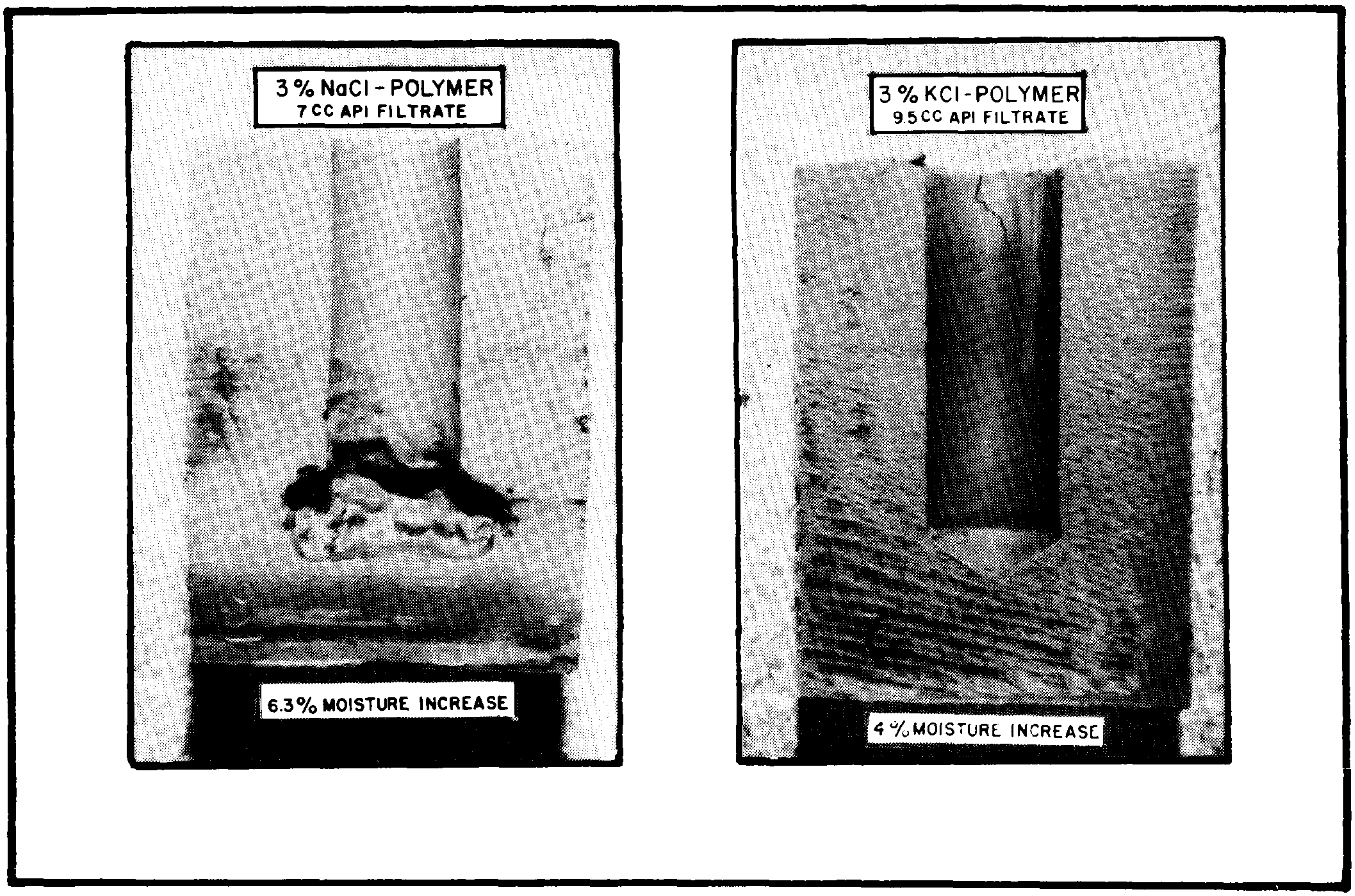

FIG. 5 — TYPE OF SALT AND MEASURED FILTRATION RATE VS. WATER ABSORPTION AND STABILITY OF SHALE

different effects of the two different salts.

Quality of Filtrate

Filtrate quality in water-base muds may be characterized in terms of the concentration and type of materials dissolved in the filtrate. In general, such materials include dispersants (e.g., lignosulfonates, lignites and tannins), and inorganic salts such as sodium chloride, potassium chloride and gypsum. Dispersants tend to accelerate the disintegration of shale; both shale at the borehole wall and shale cuttings dislodged by the bit. The inorganic salts mentioned above retard, or may even prevent, the disintegration process.

The effect of filtrate quality on hole stability was suggested earlier in Fig. 2, and is illustrated further in Fig. 6. Normally, it would be expected that a fresh-water filtrate containing dispersant would have a greater destabilizing effect on shale than a fresh-water filtrate without dispersant. The apparent anomaly indicated by the two fresh-water muds in Fig. 6 may be attributed to differences in degree of pressure underbalance. The fresh-water dispersed mud of 14.0-14.3 ppg provides mud pressures of 8880-10,410 psi over the depth interval in question (12,200-14,000 ft), while the fresh-water nondispersed mud provides pressures of only 7930-9680 psi over the same interval.

Improved stability of the hole drilled with salt polymer mud in Fig. 6 is attributed to restriction of water-wetting of the shale by both salt and polymer. The salt in this case came from locally available brine sources that are predominantly sodium chloride, but contains significant quantities of potassium and calcium ion as well. The mechanism by which shale-wetting is inhibited through a saline filtrate is thought to be osmotic, with the clay in the shale serving as semipermeable membrane.[7] Attempts to dehydrate shale with highly saline muds in the laboratory, however, have been unsuccessful.

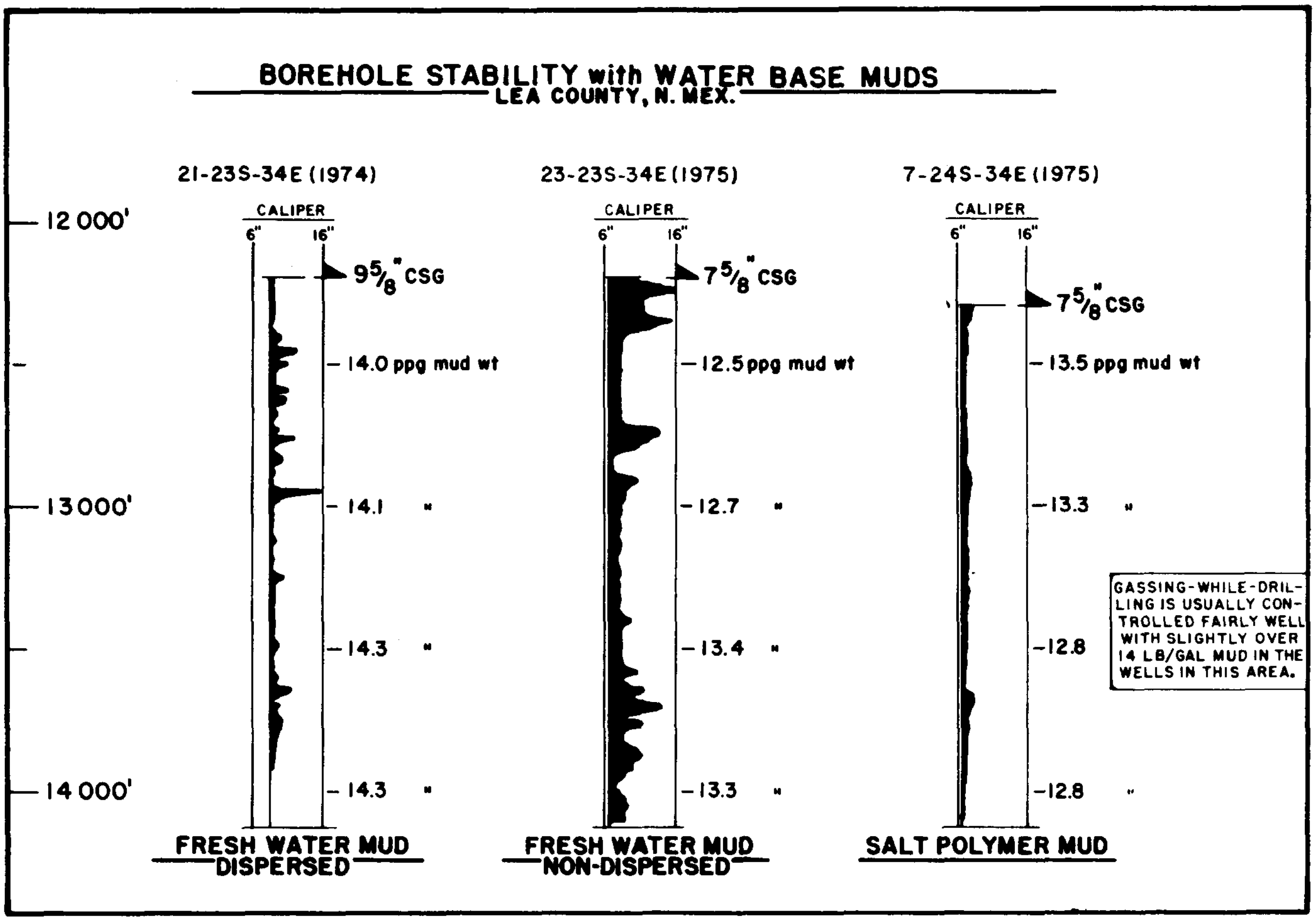

FIGURE 6

The function of selected polymers in shale stabilization is to further restrict water-wetting by mechanically plugging the openings in the surface of the shale through which water would be inbibed.[6,8] Polymer qualities that retard shale-wetting may be different from qualities that provide optimum measured filtration rate control.

Potassium Ion and Shale Stability

Special mention should be made of potassium in the filtrate of water-base mud because of the special relationship between the cation of this metal and the clays in shale. The basic mechanisms through which potassium is thought to stabilize shale have been cited in earlier papers.[9,10] Briefly, it is proposed that the diameter of the potassium ion (2.66A°) is such that it fits snugly into the voids (2.8A° diameter) on the face of the clay. It may, therefore, become "fixed" and thus hold the clay platelets together. The reaction is more likely to proceed when a higher negative charge is induced on the clay by substitution of aluminum for silicon in some of the outer layer tetrahedra. Furthermore, the hydrated diameter of potassium is relatively small, thus allowing the hydrated ion to enter easily between the clay platelets in the shale. Dimensions of ions from the group in the Periodic Table of which potassium is a member, along with other ions commonly found in drilling mud, are listed in Table 1.

The performance of potassium in stabilizing shale has been demonstrated in numerous wells, and the effectiveness of this ion for this purpose is no longer in doubt. Hole stabilization with potassium mud is illustrated in Fig. 7.[3] Precautions were taken in this case to maintain the mud free of other cations insofar as possible. Concentration of potassium ion in the filtrate was maintained at about 20,000 ppm. Note that a fairly stable hole resulted in this well, even at an apparently underbalanced condition of significant magnitude in parts of the hole.

It has been observed in the laboratory that other ions in the mud filtrate often interfere with the performance of potassium. For example, shale stabilization with potassium-treated seawater mud

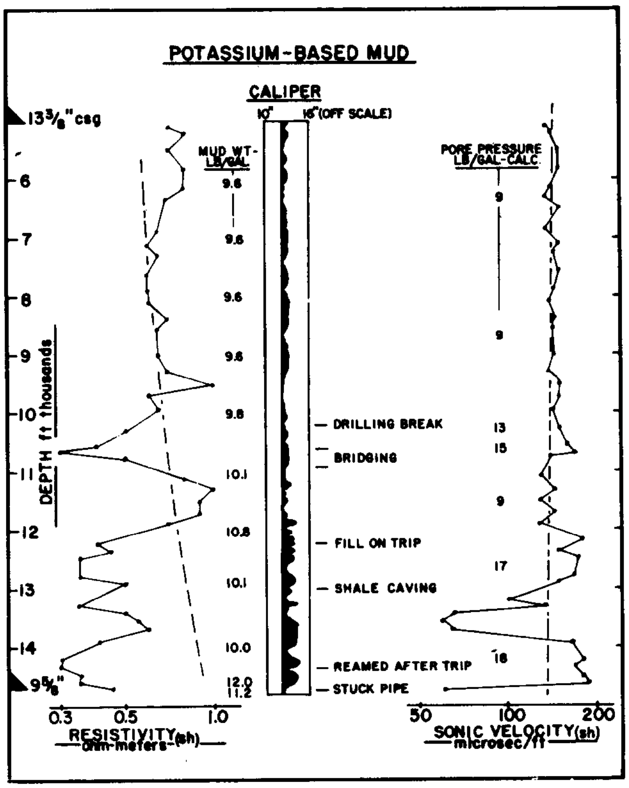

FIG. 7 HOLE STABILITY WITH POTASSIUM-BASED MUD, OFFSHORE LOUISIANA.

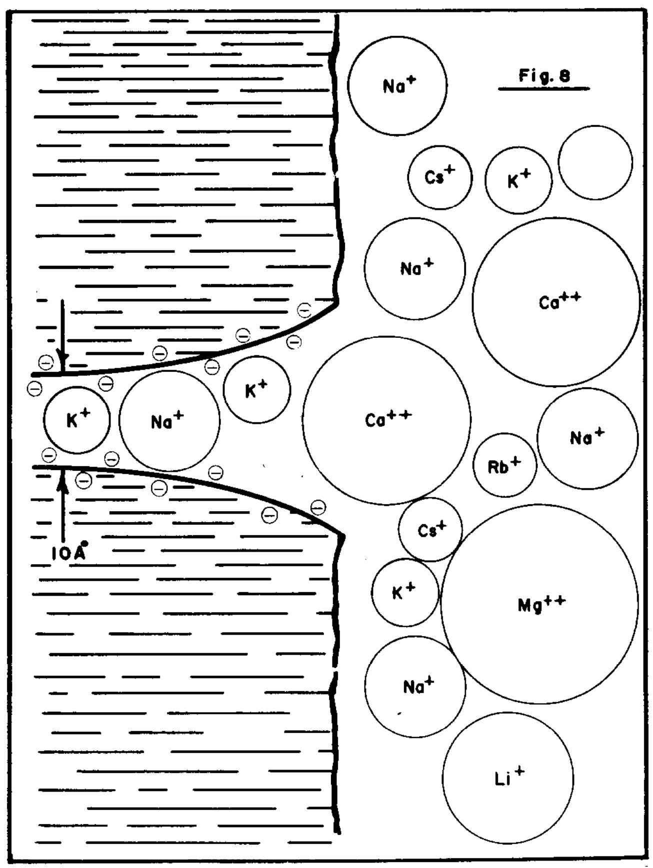

FIG. 8 "FRAYED EDGE"-INCIPIENT OPENING BETWEEN TWO CLAY PLATELETS IN SHALE AT THE BOREHOLE WALL-WITH HYDRATED CATIONS (TO SCALE).

is improved when calcium and magnesium are treated out, and a filtrate containing sodium chloride requires a higher potassium ion concentration to obtain shale stability than the filtrate without sodium chloride. Basis for speculation toward explanation of these phenomena may exist in Fig. 8, where incipient parting of clay platelets at the borehole wall are depicted along with hydrated cations that may be present in the mud. Closing of the "frayed edge"[11] would stabilize the shale, and further opening would lead to destabilization. It may be argued, for example, that a high concentration of sodium ions in the filtrate could interfere mechanically with potassium "fixation", and that calcium and magnesium could promote further opening because of the large diameter of the hydrated cation plus the high affinity of the polyvalent cation for the clay surface.[12]

OSMOTIC EFFECTS

There is one extremely important approach to borehole instability through the drilling fluid that is not readily described in terms of the usual fundamental mud characteristics. The approach in question is through salinity - controlled oil mud. The mechanism by which shale stabilization is effected by this type of drilling fluid is well-defined, and performance has been thoroughly documented in the field. The mechanism has been defined as *osmosis*[13] and as *balanced-activity*.[14] With salinity-controlled oil mud, the water content of shale in-place may actually be reduced, while with water-base muds, shale control is brought about by reducing only the rate at which the water content increases.

TABLE I

ION	*ION DIAMETER-Å	ION DIAMETER Å hydrated	HYDRATION ENERGY kcal/mol
Li^+	1.20	14.6	124.4
Na^+	1.90	11.2	97.0
K^+	2.66	7.6	77.0
Rb^+	2.96	7.2	71.9
Cs^+	3.34	7.2	66.1
Ca^{++}	1.98	19.2	377
Mg^{++}	1.30	21.6	459
NH_4^+	2.16	-	72.5

*There is some variation in the figures for hydrated diameters found in the literature.

Performance of salinity-controlled oil mud is illustrated in Fig. 2. Salinity of the water phase in this case was maintained at about 350,000 ppg $CaCl_2$. Note that a stable hole was obtained with this mud type at about 5000 psi underbalance.

SUMMARY

1. Alleviation of drilling problems through the drilling fluid may be approached systematically in terms of the weight, rheology and filtrate . . . . plus some special characteristics of the drilling fluid.
2. As an example, the problem of borehole instability was analyzed in this manner.
3. When other drilling problems are approached in the same way, it may be expected that guidelines to solutions will be indicated . . . . . insofar as it is within the capability of the drilling fluid to provide them.

REFERENCES

1. Bartlett, L.: Planned Pressure Drilling Pays Dividends. *Petr. Eng.*, July 1968, pp. 76-82.
2. Reid, C.A.: Here Are Drilling Fluids Being Used in Permian Basin's Pressured Formations. *Oil & Gas Jour.*, Apr. 27, 1970, pp. 80-83.
3. Gray, G.R., and Tschirley, N.K.: Drilling Fluids Program for Ultra-Deep Wells in the United States. Proc. IX. Petr. Congress (1975), Applied Science Publishers, Barking-Essex, England.
4. Wallace, W.E.: Abnormal Subsurface Pressures Measured from Conductivity or Resistivity Logs. *Oil & Gas Jour.*, July 5, 1965, pp. 102-105.
5. Fertl, W.H., and Timko, D.J.: How Downhole Temperatures, Pressures Affect Drilling. *World Oil*, Sept. 1972, pp. 45-50.
6. Simpson, J.P.: Drilling Fluids - Today and Tomorrow. *Jour. Petr. Tech.*, Nov. 1971, pp. 1294-1298.
7. Jones, P.H.: Hydrodynamics of Geopressure in the Northern Gulf of Mexico Basin. *Jour. Petr. Tech.*, July 1969, pp. 803-810.
8. Kennedy, J.L.: New Mud Holds Shales, Allows Fast Drilling in West Texas. *Oil & Gas Jour.*, May 29, 1972, pp. 41-44.

9. Mondshine, T.C.: Tests Show Potassium-Mud Versatility. *Oil & Gas Jour.*, April 22, 1974, pp. 120-130.
10. O'Brien, D.E., and Chenevert, M.E.: Stabilizing Sensitive Shales with Inhibited, Potassium-Based Drilling Fluids. *Jour. Petr. Tech.*, Sept. 1973, pp. 1089-1100.
11. Sawhney, B.L.: Selective Sorption and Fixation of Cations by Clay Minerals. *Clays and Clay Minerals, 20* (1972), pp. 93-100.
12. Vold, M.J. and R.D.: "Colloid Chemistry." (1964), Van Nostrand Rheinhold Publishing Co.
13. Mondshine, T.C.: New Technique Determines Oil-Mud Salinity Needs in Shale Drilling. *Oil & Gas Jour.*, July 14, 1969, pp. 70-75.
14. Chenevert, M. E.: Shale Control with Balanced-Activity Oil-Continuous Muds. *Jour. Petr. Tech.*, Oct. 1970, pp. 1309-1316.