Abnormal Formation Pressure and Shale Porosity

HALFDAN CARSTENS[2] and HENNING DYPVIK[3]

ABSTRACT

An abnormally pressured Jurassic shale from the North Sea Viking graben has a fluid pressure-overburden ratio close to 0.8 at a depth of more than 4,000 m and is associated with low porosity and high density. The porosity and fluid pressure history of the shale involves three successive stages: (1) normal gravitational compaction prevailed during the first few hundred meters of burial; (2) the shale porosity was severely reduced by carbonate cementation in conjunction with a major break in sedimentation, but the fluid pressure remained hydrostatic; and finally, (3) the porosity was further reduced by "compaction" and possibly cementation, and the fluid pressure increased to above hydrostatic in response to renewed subsidence and the Cretaceous and Tertiary overburden load.

INTRODUCTION

Abnormally pressured shales are associated with higher than "normal" porosity (Rubey and Hubbert, 1959; Stuart, 1970; Smith, 1971; Bishop, 1979). This principle of undercompaction is critical, as it forms the basis for many of the techniques applied in formation-pressure detection and evaluation. However, Bradley (1975, p. 963) questioned the general validity of this association: ". . .a complete range of high-normal-low densities is associated with abnormal pressures (D. E. Powley, 1973, personal commun.). Perhaps then, densities and pressures are not related directly." Dickey (1976, p. 1126), in a discussion of Bradley's paper, disregarded this: ". . .the statement needs substantiation in view of the almost universally accepted association of low shale densities and high pressures," and "Measuring porosity of shale is now an almost universal method of detecting high-pressure zones all over the world. It seems to be successful in Tertiary basins such as those of Nigeria and southeast Asia. It also is used in Mesozoic rocks such as those of the McKenzie delta, the northwest shelf of Australia and the North Sea."

Bradley (1976, p. 1128) in his reply to Dickey, gave examples of density and formation pressure data from four United States wells but gave no details which contribute to a better geologic understanding of the phenomenon that: ". . .abnormal pressures may be associated with a complete range of densities."

The scope of our study is to describe a North Sea shale sequence in which the onset of abnormal formation pressures does not seem to be coincident with any increase in shale porosity, and to discuss the geologic history which gave rise to this phenomenon.

Plumley (1980) demonstrated, for a Tertiary shale of the Gulf of Mexico, the occurrence of lower porosity than should be expected for a given formation pressure if undercompaction were the sole cause of the overpressuring, but this was attributed to the mechanisms that generate abnormally high pressures, rather than the lithification history of the shale.

Several techniques applied in formation-pressure detection are based on the theory that high pressures are associated with high porosity (Hottman and Johnson, 1965; Lewis and Rose, 1970). If this principle does not hold true in a specific formation or sedimentary basin, it has important implications for what are termed "porosity tools" and was outlined in greater detail by Carstens and Dypvik (1979).

REGIONAL GEOLOGY

The well studied is located in the northern North Sea basin (Fig. 1), in the area of the giant Brent and Statfjord oil fields. Basin subsidence was initiated in late Paleozoic time as a consequence of a possible failed rift system which can be recognized in the larger Northwest European basin. Subsidence continued throughout the Mesozoic and Cenozoic, but sedimentation was interrupted by several breaks, which may have been caused by major eustatic sea-level variations (Vail et al, 1977). Block faulting in Jurassic time formed what are now the main prospective traps in the northern North Sea.

Thick continental arenaceous deposits of Triassic to Early Jurassic age are succeeded in the area by marine shales and Middle Jurassic deltaic sandstones. The overlying Upper Jurassic black shales constitute the dominant source rock of the northern North Sea. The base of the Cretaceous unconformity is an outstanding feature, which has been correlated all over the basin, except for perhaps the deeper axial parts. Sedimentation in Cretaceous time resulted in thick shale sequences with only subordinate carbonate and sandstone stringers. Early Tertiary uplift of the basin margins gave rise to localized sand influx into a relatively deep-water basin characterized by "gumbo clays." The intra-Oligocene unconformity

[1]Manuscript received, May 19, 1980; accepted, September 2, 1980.
[2]Saga Petroleum a.s., N-1301 Sandvika, Norway.
[3]Institutt for Geologi, Universitetet i Oslo, Blindern, Oslo 3, Norway.

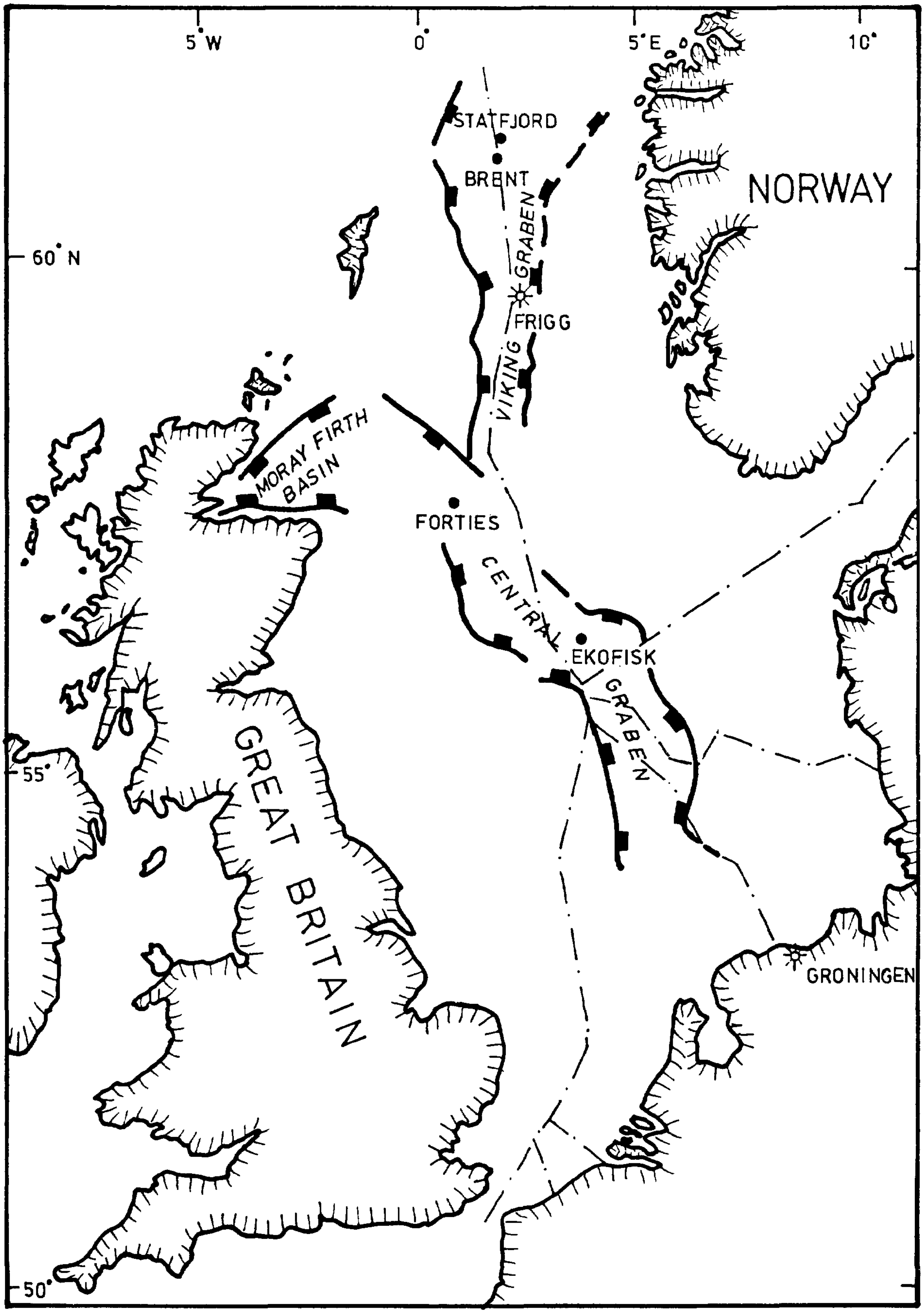


FIG. 1—North Sea basin, major structural units. Well discussed is in northern part of Viking graben.

forms another correlation horizon with upper Tertiary and Quaternary clays and sands above (Fig. 2).

Formation pressures in the northern North Sea range from normal hydrostatic to geostatic pressures. The Triassic and Jurassic reservoir rocks show systematic variations according to location and structural position. In the deeper Viking graen, pressure gradients exceed 20 kPa/m (0.88 psi/ft) at depths greater than 4,000 m whereas values of 15 kPa/m (0.66 psi/ft) are more common in the structurally shallower parts (Fig. 3). Drilling data and wireline logs show the Cretaceous shales to be overpressured. A gradual increase in pressure gradient from top to bottom is normally assumed. As for the Tertiary, abnormal pressures have been generated in the low-permeability smectite clays ("gumbo") of the lower Tertiary. Normal hydrostatic pressures prevail in the sandy and silty sections above.

For a more detailed introduction to North Sea stratigraphy, basin development, and petroleum potential, refer to Kent (1975) and Ziegler (1978, 1979).

NORTH SEA EXAMPLE

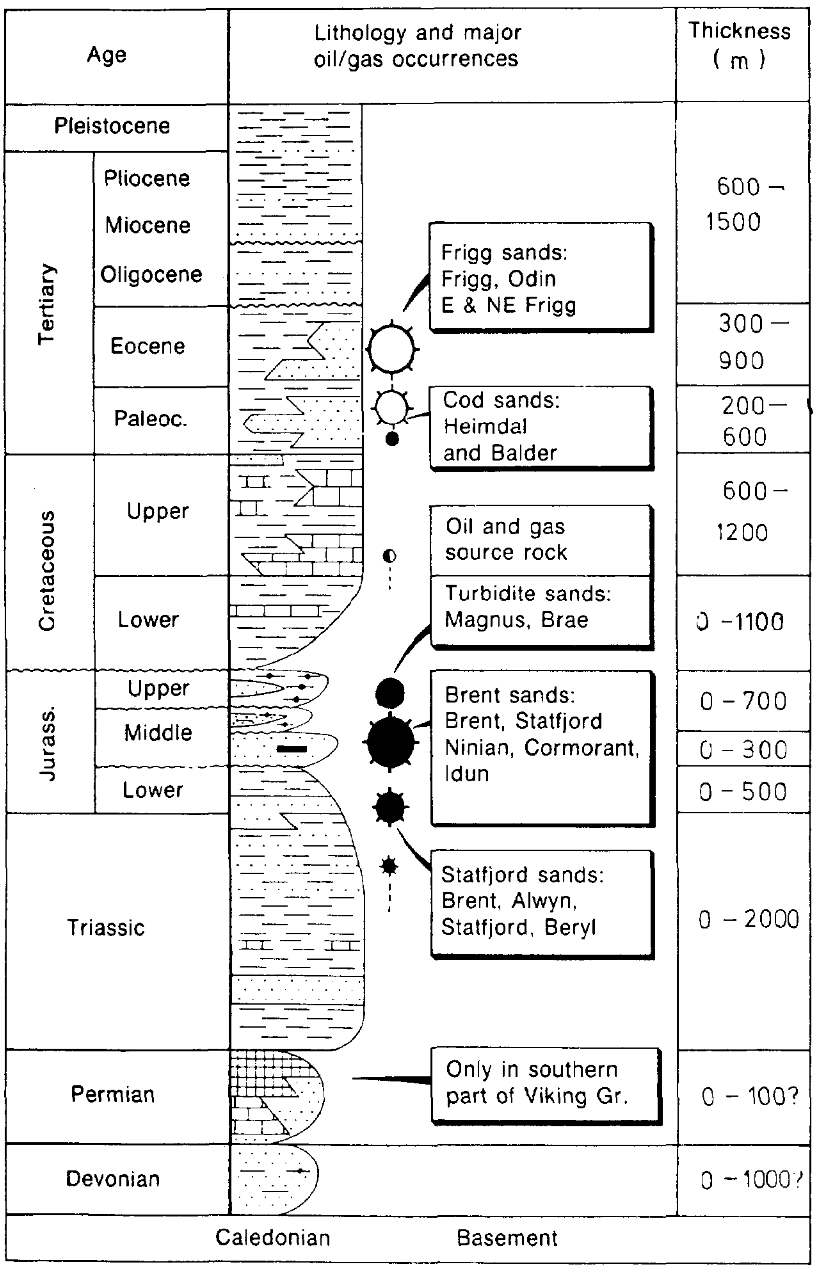
Fluid Pressure Versus Bulk Density

The well studied penetrated almost 4,000 m of Cretaceous to Tertiary claystones, shales, and sandstones of mostly normal hydrostatic pressures, except for a modest pressure buildup in the deeply buried Lower Cretaceous series. A rapid increase in fluid pressure gradient is evident at the base of the Cretaceous unconformity and in the Middle to Upper Jurassic shales. The pore fluid pressures in the bottom part of the well approach 17 kPa/m (0.75 psi/ft) which equals a fluid pressure-overburden ratio close to 0.8 at this depth (Fig. 4). The overburden gradient is determined by integrating the density-log values, and is less than 23 kPa/m (1 psi/ft).

Figure 4 shows a formation-density plot which demonstrates both the high density-low porosity and the lack of any density reversal in the transition zone. Low porosity of the shales is confirmed by petrographic analyses.

Depositional and Diagenetic History

During the Late Jurassic prodeltaic sedimentation of silty clays



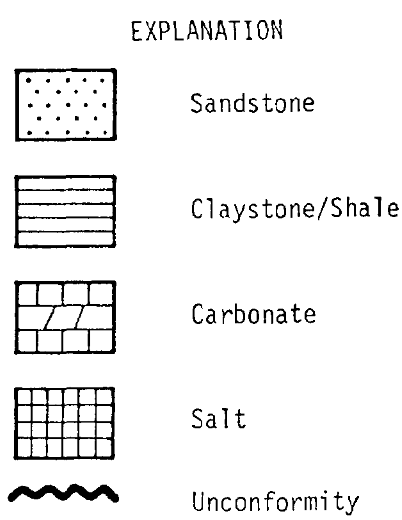


FIG. 2—Generalized stratigraphic sequence of northern North Sea (from Ziegler, 1979).

occurred in the study area. Several periods of nondeposition formed minor breaks in the succession. A major break accompanied by uplift between the Oxfordian and Aptian was succeeded by the more continuous, marine Cretaceous clay sedimentation. Minor episodes with sand sedimentation (storm generated?) disrupted the clay sedimentation during this period.

Petrologic analyses (X-ray diffraction, thin section, scanning electron microscopy) show the presence of cement and diagenetically formed minerals. In the shales and sandstones analyzed, framboidal pyrite, delicate booklets of kaolinite, overgrowth of quartz, and microsparitic carbonate cement of obvious diagenetic origin are present (Figs. 5-8). The analyses show the following general diagenetic evolution: (1) pyrite, (2) quartz overgrowth, (3) kaolinite, (4) carbonates (dolomite, siderite).

In the Jurassic shales all four major types of cement and diagenetic minerals are present whereas, in the Cretaceous shales, generally only pyrite, quartz overgrowth, and kaolinite are present.

Soon after deposition, pyrite was formed in reducing conditions in the Jurassic sediments (Fig. 5). In addition, quartz overgrowth is thought to be of early diagenetic origin, but mainly somewhat later than the pyrite (Fig. 7). The quartz may have been precipitated owing to the pH contrast between fresh and saline waters in deltaic environments (Fisher et al, 1974). This cement and the later precipitated pore-filling kaolinite (Fig. 6) are probably of minor importance in the porosity reductions. The quartz and kaolinite cement was probably deposited during breaks in sedimentation and minor periods of upheaval, when silica- and alumina-enriched waters could percolate. The major porosity and permeability reductions are thought to be connected with the Jurassic-Cretaceous break, when the microsparitic carbonate cement most probably was formed (Fig. 8). During that period of uplift and nondeposition, renewed water circulation in the sediments may have resulted in Dorag dolomitization (Badiozamani, 1973) and sideritization of carbonates in the slightly permeable Jurassic silty clays and claystones. Some sideritization may also have occurred during burial, as burial to about 1 km depth may permit decarboxylation of organic matter and siderite formation (Tourtelot, 1979).

After the Oxfordian-Aptian break in sedimentation, more continuous sedimentation of clays started during the Cretaceous. Diagenetic formation of pyrite, quartz overgrowth, and kaolinite occurred only in some minor sand horizons.

Porosity Evolution and Pressure Buildup

The just outlined diagenetic history suggests that both gravitational compaction and cementation have reduced the pore space of the Jurassic shales (Fig. 9). Initially, gravitational compaction, following deposition in Jurassic time, reduced the porosity exponentially by ordering and rearrangement of the clay particles (Hedberg, 1936; Meade, 1966). At an early stage of burial pyrite and, somewhat later, diagenetic quartz and kaolinite were precipitated, resulting in only modest porosity losses. Owing to rather shallow burial (<1,000 to 1,500 m) these clays probably did not generate pore pressures much higher than the hydrostatic pressures (c.f., Bishop, 1979).

The characteristic carbonate cement (siderite, dolomite) was most likely formed in conjunction with a major break in sedimentation from

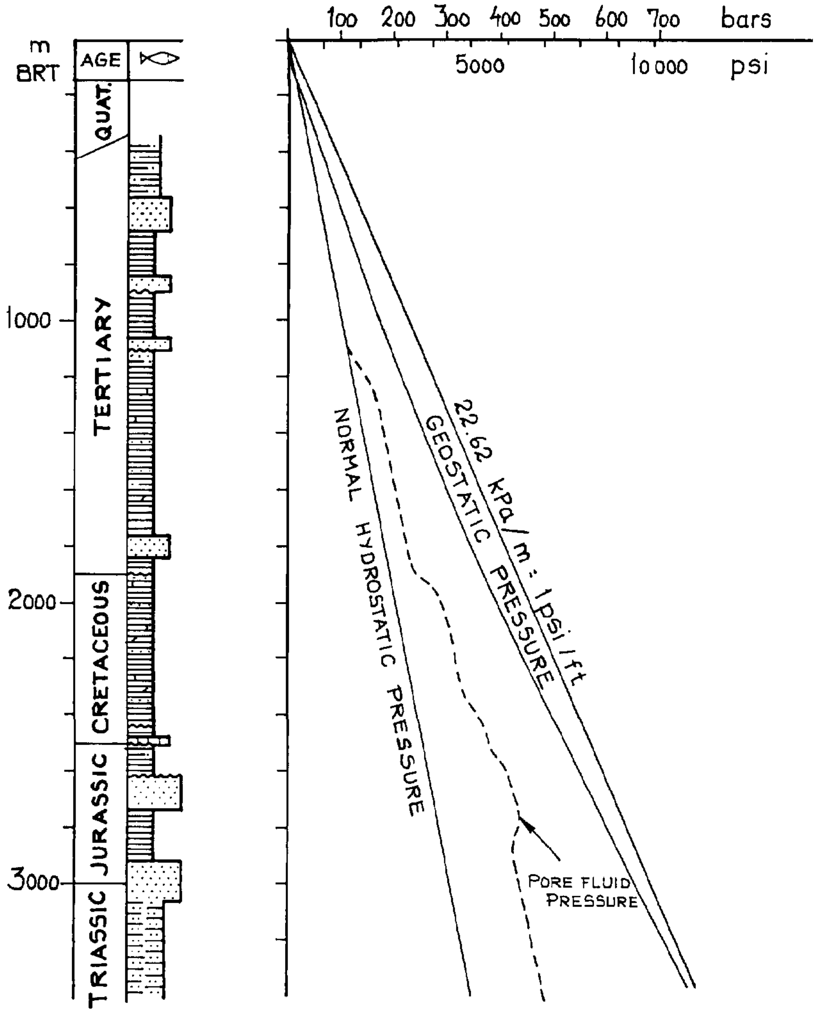


FIG. 3—Typical formation pressures versus stratigraphy and lithology of northern North Sea well. Stratigraphic symbols are same as in Figure 2.

Oxfordian to Aptian, reducing the porosity considerably. This time episode would have reduced any preexisting abnormal pressures in the sequence (cf., Smith, 1971).

When basin subsidence and sedimentation were renewed in late Early Cretaceous time, thick Cretaceous and Tertiary deposits were deposited continuously, and porosity was further reduced by "compaction" and some sideritization. However, the true nature of this process remains unknown, as the shales had probably already gone through a rearrangement of the clay minerals, and diagenetic minerals would have restricted any further ordering owing to reduced porosity. Because of low porosity and hence low permeability, the shales were now "self sealing" (Rubey and Hubbert, 1959). Owing to either the overburden load or to aquathermal pressuring (Barker, 1972) or both, the pore fluid pressure in this situation increased faster than the hydrostatic pressure.

This North Sea Jurassic shale sequence therefore exemplifies an abnormally pressured shale with low porosity and corresponding high density. A geologic explanation for this little-reported phenomenon is attempted from detailed petrographic studies and is combined with a suggested fluid pressure buildup history.

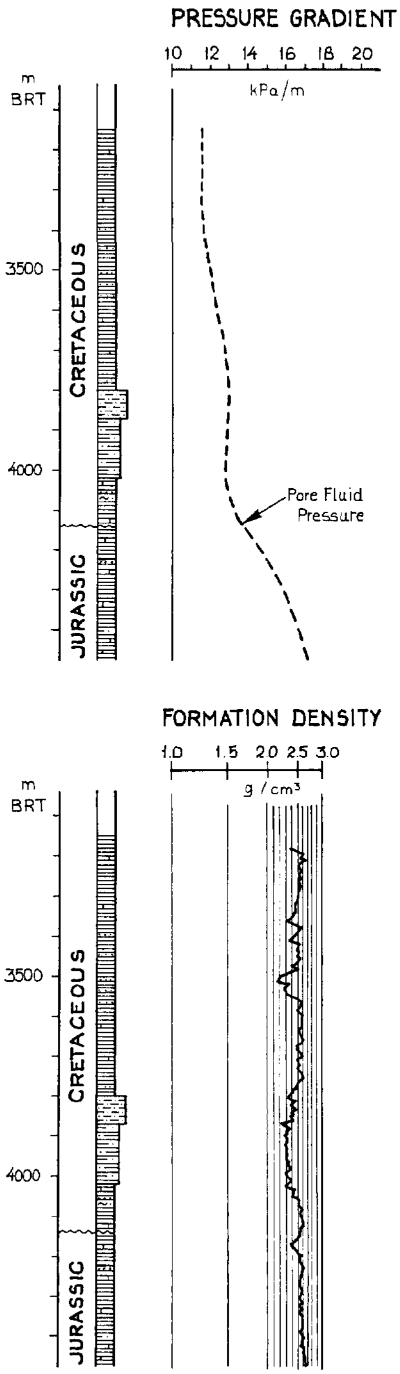


FIG. 4—Pore fluid pressure and formation density (from FDC-log) versus depth, age, and lithology. There is no density reversal at onset of increased pressure gradients in Jurassic. Stratigraphic symbols are same as in Figure 2.

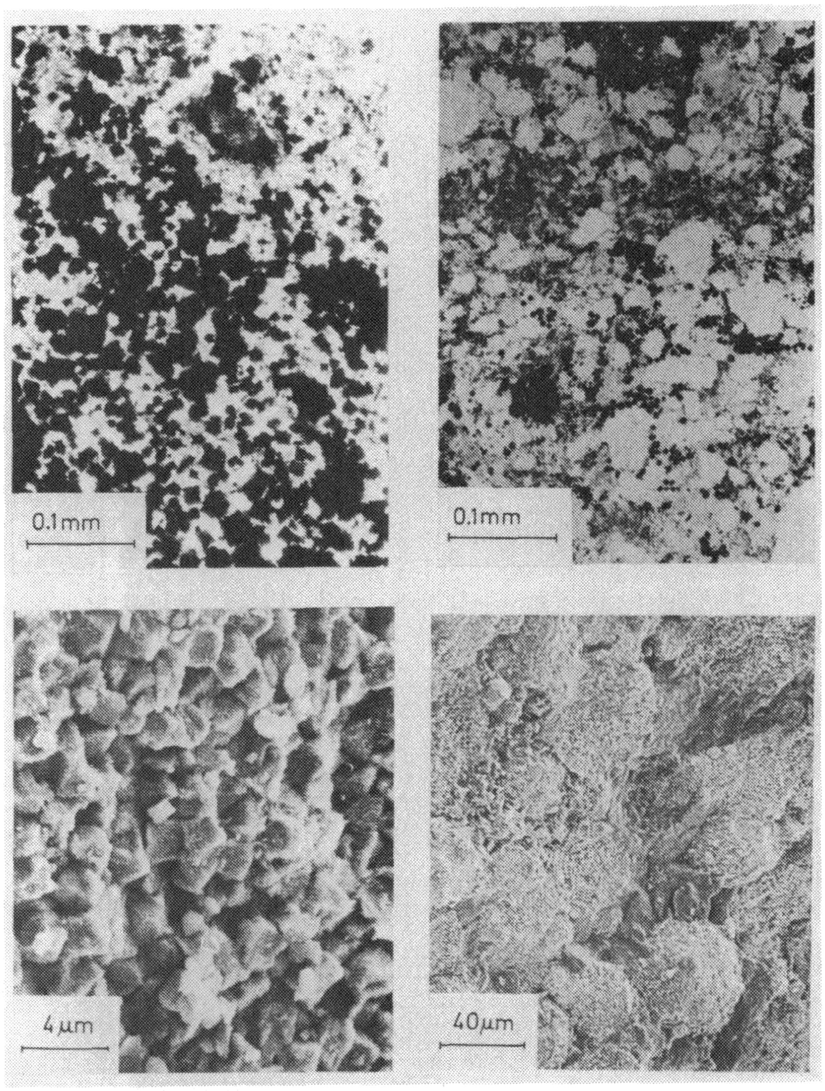


FIG. 5—Framboidal pyrite from Mesozoic sediments in thin section (upper) and SEM (lower).

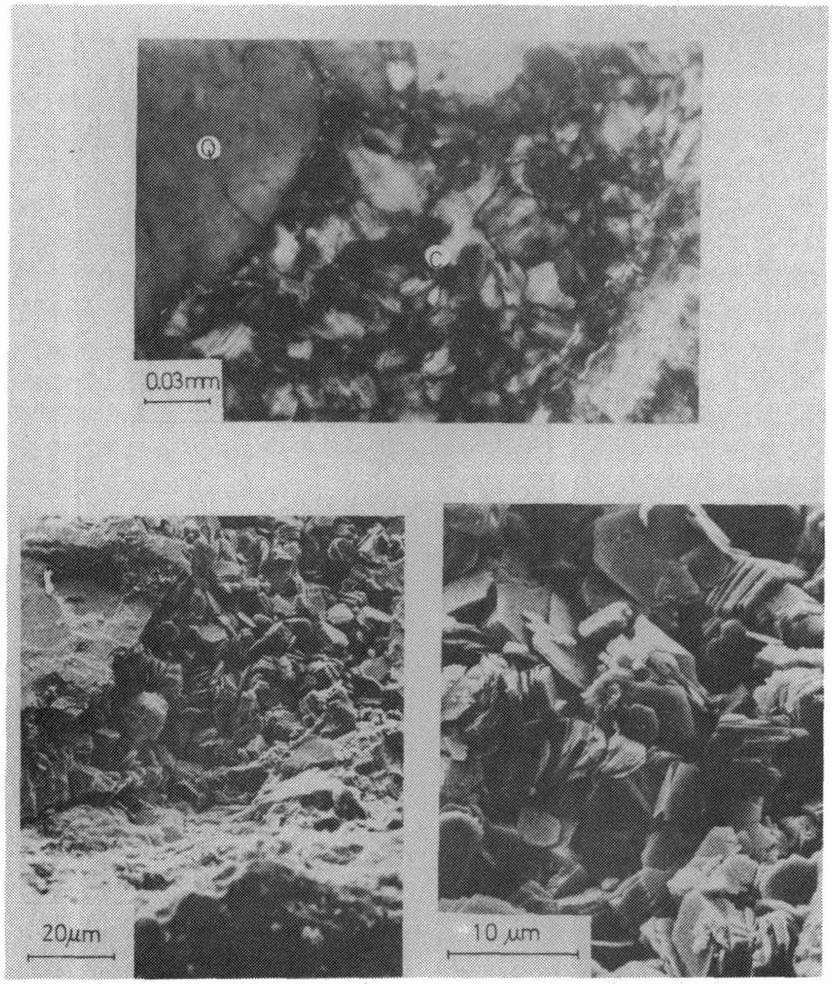


FIG. 6—Photomicrographs of thin section (upper half) showing pore-filling kaolinite, C. Two lower SEM photographs show delicate booklets of pore-filling kaolinite.

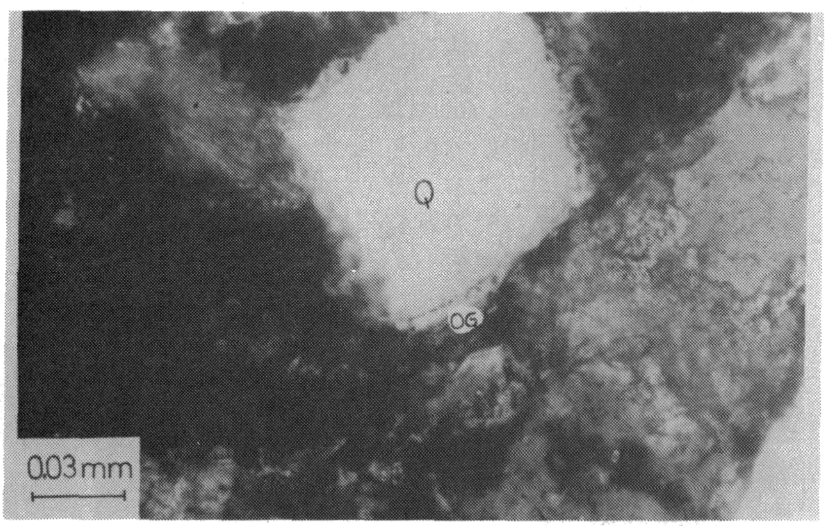


FIG. 7—Photomicrograph of thin section showing quartz grain, Q, with overgrowth, OG indicated by dustline.

CONCLUSION

The study presented herein gives credibility to the statement of Bradley (1975, 1976) that abnormal formation pressures may be associated with a complete range of high-normal-low densities. Moreover, we are able to outline a geologic and pressure buildup history that gave rise to high pressure and high density associations in the North Sea study sequence.

The general belief that overpressured formations are characterized by higher than normal porosity has evolved for the Gulf of Mexico Cenozoic basin (cf., Stuart, 1970) and has gained wide acceptance for many other basins. Detailed geologic studies that justify this acceptance are limited.

The geologic history of the Gulf of Mexico Cenozoic basin is relatively simple with rather continuous deposition and subsidence of prograding series transected by growth faults. Compaction of deep-water clays was restricted owing to their "self-sealing" capacity, resulting in a high water content, even at great depths. The North Sea basin, however, has gone through a much more complicated tectosedimentologic evolution, which is manifested in a more variable lithologic development, major unconformities at several stratigraphic levels, and a more complicated structural definition. These are all factors that will influence the lithification history of the claystones and shales and hence the relation between overpressuring and porosity.

We believe that studies like the present one are of significance in understanding the chemical and physical characteristics of overpressured formations, which ultimately may improve the methods used in formation pressure detection.

REFERENCES CITED

Badiozamani, K., 1973, The Dorag dolomitization model—application to the Middle Ordovician of Wisconsin: Jour. Sed. Petrology, v. 43, p. 965-984.

Barker, C., 1972, Aquathermal pressuring—role of temperature in development of abnormal-pressure zones: AAPG Bull., v. 56, p. 2068-2071.

Bishop, R. S., 1979, Calculated compaction states of thick abnormally pressured shales: AAPG Bull., v. 63, p. 918-933.

Bradley, J. S., 1975, Abnormal formation pressure: AAPG Bull., v. 59, p. 957-973.

_____ 1976, Abnormal formation pressure: reply: AAPG Bull., v. 60, p. 1127-1128.

Carstens, H., and H. Dypvik, 1979, Prediction, detection and evaluation of abnormal formation pressures in virgin areas: some limitations: Norwegian Petroleum Soc. Paper NSS 13, 14 p.

Dickey, P. A., 1976, Abnormal formation pressure: discussion: AAPG Bull., v. 60, p. 1124-1127.

Fisher, W. L., et al, 1974, Delta systems in the exploration of oil and gas: Austin, Texas, Univ. Texas Press, p. 77.

Hedberg, H. D., 1936, Gravitational compaction of clays and shales: Am. Jour. Science, v. 31, p. 241-287.

Hottman, C. E., and R. K. Johnson, 1965, Estimation of formation pressures from log-derived shale properties: Jour. Petroleum Technology, v. 17, p. 717-722.

Kent, P. E., 1975, Review of North Sea basin development: Geol. Soc. London Jour., v. 131, p. 435-468.

Lewis, C. R., and S. C. Rose, 1970, A theory relating high temperatures and overpressures: Jour. Petroleum Technology, v. 22, p. 11-16.

Meade, R. H., 1966, Factors influencing the early stages of the compaction of clays and sands—review: Jour. Sed. Petrology, v. 36, p. 1085-1101.

Plumley, W. J., 1980, Abnormally high fluid pressures: survey of some basic principles: AAPG Bull., v. 64, p. 414-430.

Rubey, W. W., and M. K. Hubbert, 1959, Role of fluid pressure in mechanics of overthrust faulting, pt. II: Geol. Soc. America Bull., v. 70, p. 167-206.

Smith, J. E., 1971, Shale compaction: Soc. Petroleum Engineers Paper 3633, 12 p.

Stuart, C. A., 1970, Geopressures: 2d Symposium Abnormal Subsurface Pressures, Proc., suppl., 121 p.

Tourtelot, H. A., 1979, Black shale—its deposition and diagenesis: Clays and Clay Minerals, v. 27, p. 313-321.

Vail, P. R., R. M. Mitchum, and R. G. Todd, 1977, Eustatic model for the North Sea during the Mesozoic: Norwegian Petroleum Soc. Paper MNNSS 12, 35 p.

Ziegler, P. A., 1978, North-Western Europe. Tectonics and basin development: Geologie en Mijnbouv, v. 57, p. 589-626.

_____ 1979, Factors controlling North Sea hydrocarbon accumulations: World Oil, v. 189, Nov., p. 111-124.

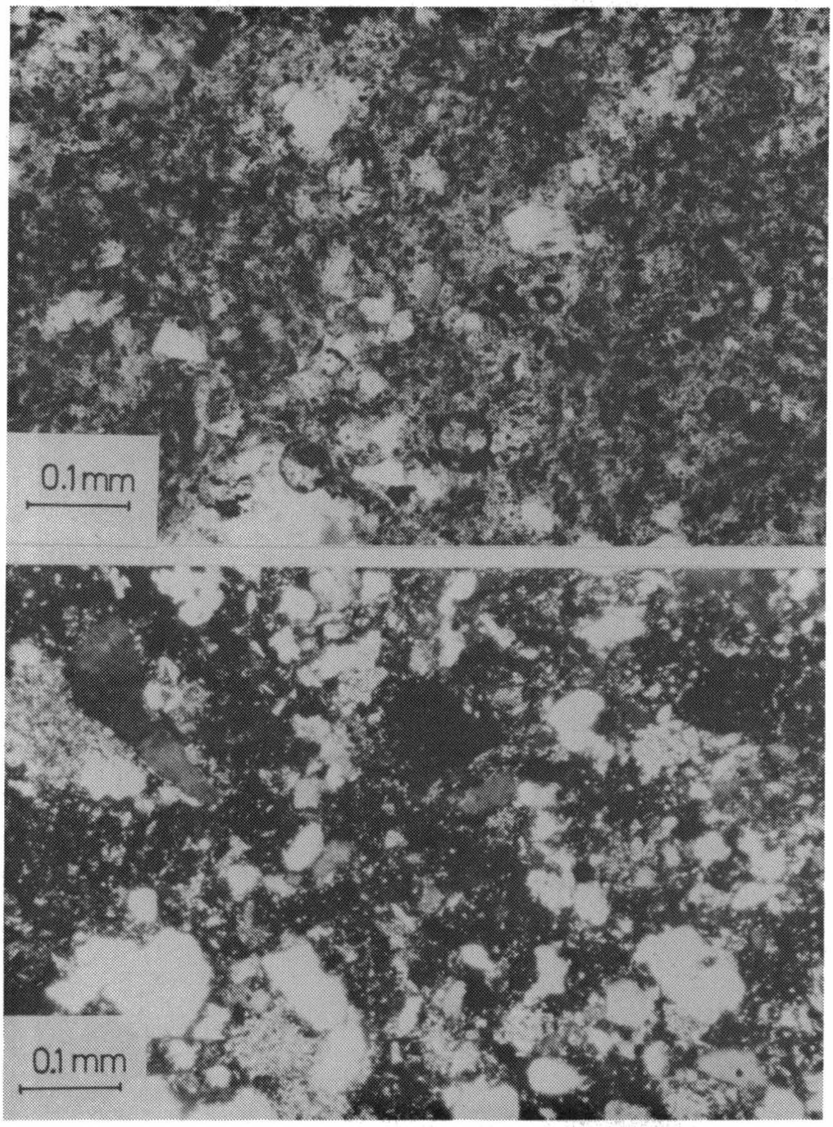


FIG. 8—Photomicrographs of thin section; upper typical Cretaceous shale; silty, Jurassic shale with dispersed rhombs of carbonate cement.

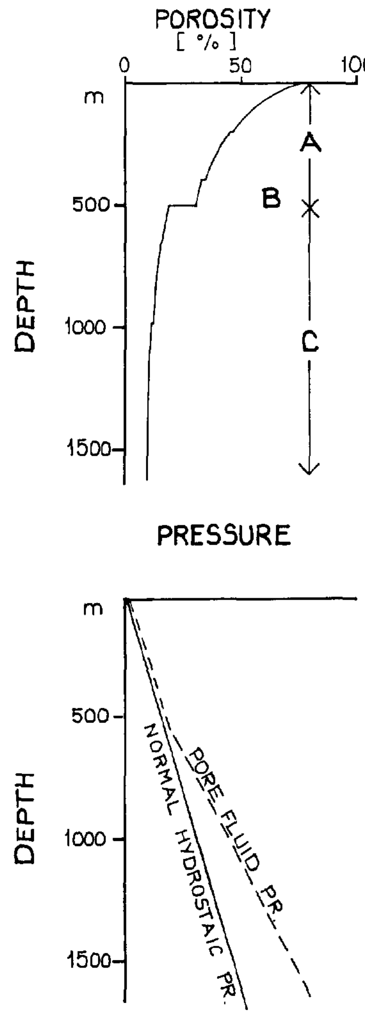


FIG. 9—Schematic porosity evolution and pressure buildup model for one element of Jurassic deposits. Stage A: mechanical rearrangement of clay minerals, minor porosity reduction by cementation indicated; normal hydrostatic pressures. Stage B: cementation in conjunction with Oxfordian-Aptian break; normal hydrostatic pressures. Stage C: porosity loss in response to Cretaceous and Tertiary overburden, sideritization indicated; pore fluid pressure buildup. Stages of uplift and erosion are not indicated.