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Aquathermal Pressuring—Role of Temperature in Development of Abnormal-Pressure Zones[1]

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Abstract Zones of abnormal subsurface pressures, both above and below hydrostatic, have been described in many areas. The very abrupt changes in pressures and salinities, together with the undercompacted nature of the high-pressure zones, indicate that they are effectively isolated from their surroundings. If this isolation occurred at a shallower depth than the present one, the isolated volume would have been subjected to increasing temperatures as it moved downward. The *P-T*-density diagram for water shows that, for any geothermal gradient greater than about 15°C/km, the pressure in an isolated volume increases with increasing temperature more rapidly than that in the surrounding fluids. This mechanism for producing excess pressures will operate in addition to most of the other processes that have been suggested, but the overall influence in any given area will depend on how well the system remains isolated. If a normally pressured system becomes isolated and is then subjected to a decrease in temperature (for example, if erosion removes considerable quantities of overburden) the pressure in the system will fall below the external hydrostatic pressure. This may have happened in some areas which now have abnormally low pressures.

Zones of anomalous subsurface pressures, both above and below hydrostatic, have been described in many parts of the world. The high-pressure zones along the northern coast of the Gulf of Mexico have been particularly well studied, and there pressures as much as 5,000 psi above the normal hydrostatic values are not uncommon. These excess pressures can be expressed conveniently in terms of the geostatic ratio, which is the ratio of observed fluid pressure to the lithostatic pressure at the same depth. Normal hydrostatic pressures give a ratio close to 0.47, whereas lithostatic pressure corresponds to 1.00. High pressure zones have been encountered with geostatic ratios in excess of 0.95. Generally high-pressure zones are characterized by undercompaction in the shales, and they also commonly contain water which is less saline than the corresponding fluids outside.

In many places there is a very abrupt change from normal pressure to high pressure, indicating that the pressurized volumes are isolated from their surroundings. Dickinson (1953) concluded that "a reservoir containing high pressure must be effectively isolated from any other porous formation which contains normal hydrostatic pressure, otherwise the pressure would be dissipated."

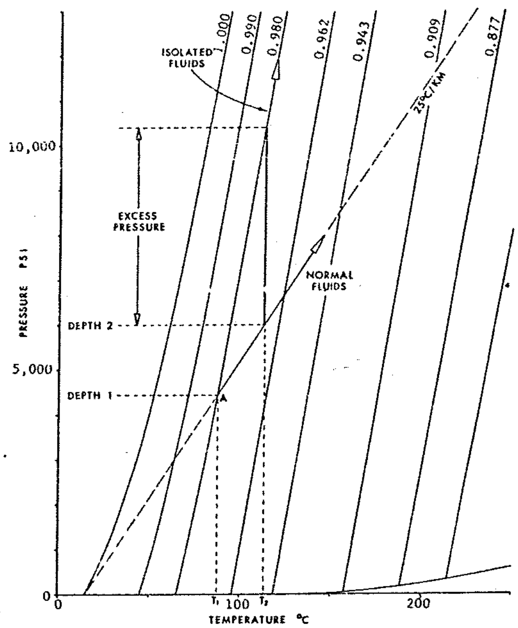

FIG. 1—Pressure-temperature-density diagram for water with superimposed geothermal gradient of 25° C/km, showing *P-T* relation for normal and isolated fluids as temperature rises.

More recently, Jones (1969) has written that, "In theory geopressured reservoirs are closed compartments having fixed or constant volume." Dickey *et al.* (1972) wrote that in Louisiana "the abnormal pressures are found only in sands completely enclosed in shale, with no permeable connection to the outcrop." Most other writers also have reached the conclusion that high pressure zones are effectively isolated from their immediate surroundings.

It is instructive to consider the time when this isolation occurred, and to investigate the consequences of such an isolation. The northern coast of the Gulf of Mexico has been an area of continuous deposition, and any isolation of a potential high pressure zone at a time significantly before

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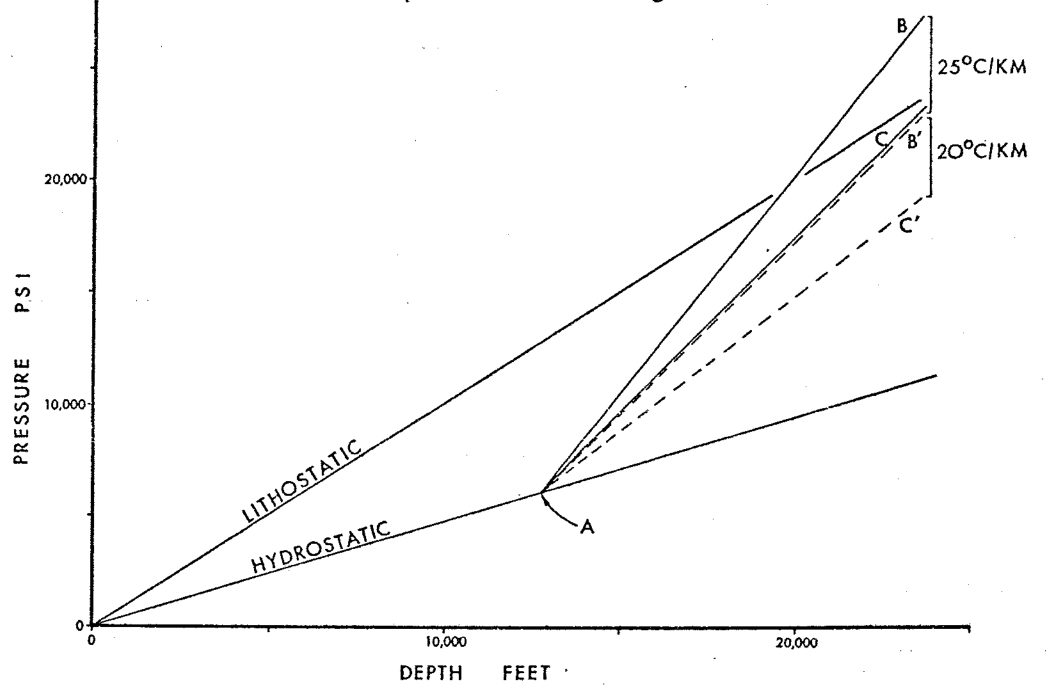

FIG. 2—Increase in excess pressure with increasing depth of burial after initial isolation at point *A*. For both geothermal gradients shown, uppermost of pair of lines *(A-B, A-B')* is for pure water and lower one (A-C, A-C') is for 30 percent sodium chloride solution.

the present means that the isolation occurred at a shallower depth than the present one. This corresponds to less compacted shales and to formation waters of lower salinity, for salinity generally increases with depth (Dickey, 1969). It also implies isolation at a temperature lower than that observed now. The effect of increasing temperature on the contents of such an isolated volume is the main topic of this note.

The pressure increase which results from increasing temperature is best considered by reference to the pressure-temperature-density diagram for water. Figure 1 shows a pressure-temperature diagram with selected isodensity lines plotted from the data given by Kennedy and Holser (1966). A geothermal gradient of 25°C/km is superimposed. This value is fairly typical for the Louisiana Gulf Coast, where reported gradients range from 18 to 36°C/km with most values lying between 22 and 24°C/km (Jam L. *et al.*, 1969). Because depth and pressure are related, the pressure and temperature of the formation fluids which follow the normal hydrostatic gradient are related by the geothermal gradient, so that for any given temperature the pressure is fixed. If, however, some of the rocks containing the fluid become isolated by material of low permeability, for example, during faulting, the isolated system becomes one of constant density because a fixed mass of material is trapped in an essentially constant volume. The pressure and temperature of the contents of the sealed volume then will be related, not by the geothermal gradient, but by one of the isodensity lines of the pressure-temperature diagram. For a given rise in temperature the pressure in the isolated volume will increase more than that in the open system. If isolation occurs at Depth 1 and T_1 (point A) and the system is then buried to Depth 2 corresponding to T_2 for this 50°-rise in temperature, the pressure in the normal formation fluids will rise to 6,000 psi. But the same temperature rise increases the pressure in the isolated volume to 10,400 psi. Thus a high-pressure zone with a pressure 4,400 psi above the normal hydrostatic value is created by a temperature increase of 50°C. This corresponds to an increased depth of burial of 3,500 ft if the geothermal gradient is 25°C/km. For higher geothermal gradients smaller increases in depth are required to cause the same increase in pressure. The term "aquathermal pressuring" is proposed for this mechanism of generating high-pressure zones.

The pressure generated aquathermally depends on how much the depth of burial increases after the volume becomes isolated, as well as on the geothermal gradient. Line A-B (Fig. 2) shows the way in which the excess pressure P increases

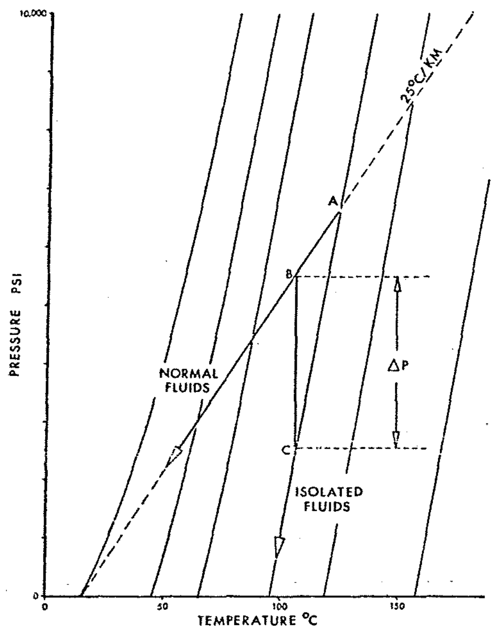

FIG. 3—Pressure-temperature-density diagram for water showing the P-T relations for normal and isolated fluids as temperature falls.

relative to the hydrostatic and lithostatic values. In this illustration trapping occurs at 12,500 ft, which is roughly 6,000 psi, and the geothermal gradient is 25°C/km. This shows that aquathermally generated pressures can exceed the lithostatic value at geologically reasonable depths and give a geostatic ratio greater than one. This is a geologically unstable condition which would be relieved by movement of some kind, possibly faulting or diapirism. Up to this point we have been using data from the phase diagram for pure water, but most waters in the subsurface are saline. The pressure-temperature-density diagrams for sodium chloride solutions closely resemble the diagram for water, but the isodensity lines are displaced to higher temperatures. With increasing depth of burial the excess pressure does not rise as rapidly for a saline solution as for pure water, and line A-C (Fig. 2) shows how the pressure increases for a 30-percent solution of sodium chloride. Real subsurface fluids lie between the extremes represented by lines A-B and A-C.

So far we have been discussing the ideal case in which the contents of the high-pressure zone remain isolated and of constant density. However, in nature it is possible that the volume, or the mass of trapped liquid, or indeed both, may change. In the first case the contents of the high-pressure zone may be isolated in the way that the contents of a balloon are isolated, so that a volume increase can occur without loss of material. If the volume increases, it will act to reduce the density and hence reduce the excess pressure. An increase in volume of about 5 percent would be enough to reduce an excess pressure of 4,000 psi back to the normal hydrostatic value. The isolated zones probably are imperfectly sealed so that some of the contents may be leaking out. This also would cause a reduction in the pressure, and an excess pressure of 4,000 psi would be reduced to the normal hydrostatic value by a 5-percent loss of material.

The shales in high-pressure zones are undercompacted compared with other shales at the same depth, so that the isolated volumes contain a greater percentage of water and are poorer conductors of heat. Therefore, it has been suggested that they can have somewhat higher temperatures than the surrounding rocks (Lewis and Rose, 1970). If this is the case, the higher temperatures will favor aquathermal pressuring within the isolated volume. The increase is approximately 200 psi per °C, so that a temperature 5° above normal is needed to generate an excess pressure of 1,000 psi.

Mineral transformations which occur with the release of water also can increase the pressure, or alternatively can provide a means of offsetting losses due to leakage. The gypsum-anhydrite conversion may be important at shallow depths, but the dehydration of montmorillonite probably becomes the most important diagenetic process as depth increases. The amount of water released is substantial and may be as much as 10 percent of the volume of the isolated sediment (Burst, 1966). The dehydration process is endothermic and needs temperatures in excess of 100°C. It would be favored by a slightly higher temperature in the high-pressure zone. In the presence of potassium ions, montmorillonite converts to illite and this process releases a volume of water equal to about half of the volume of the altered montmorillonite (Powers, 1967). As the water released by mineral transformations is fresh, it reduces the salinity of the trapped liquids.

In summary, aquathermal pressuring is a possible mechanism for generating abnormal subsurface pressures, and the effect will be enhanced by slightly higher temperatures in the high pressure zone and by mineral transformations which occur with the release of water. An increase in volume or leakage of material from the high-pressure zone will reduce the excess pressure. It is not suggested that aquathermal pressuring is responsible for all abnormally pressured zones, but it will operate whenever an isolated volume is moved down a geothermal gradient. Whether aquathermal pressuring modified by the factors discussed will produce a net increase in pressure must be evaluated separately in each area.

In addition to abnormally high pressures, areas have been described where the pressures are abnormally low, as for example in the San Juan basin. The different response of the contents of isolated and open systems to changing temperatures again may provide the explanation. If a normally pressured zone becomes effectively isolated from its surroundings (Fig. 3, point A), and if this zone then is cooled (*e.g.,* by uplift, or removal of overburden during erosion), the pressure in the isolated volume as given by A-C will fall below the normal hydrostatic value, because the contents of the isolated volume correspond to conditions of constant density and follow an isodensity line, whereas the fluids in the open system follow the geothermal gradient.

The discussion presented here makes no reference to scale. The properties discussed are independent of the volume of the system, and the treatment applies equally well to a cubic mile of fluid trapped in a sand lens as it does to a fraction of a milliliter of fluid trapped between clay particles.

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