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The American Association of Petroleum Geologists Bulletin
V. 58, No. 12 (December 1974), P. 2513-2521, 5 Figs., 1 Table

GEOLOGIC NOTES

Aquathermal Fluid Migration[1]

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Abstract A given weight of water expands in volume with increase of subsurface temperature during burial. The expansion may contribute to water movement from deep sections to shallow, or from the basin center to the margins, and thus could be a contributing factor in hydrocarbon migration. The higher the geothermal gradient, the more water expansion can be expected; a high geothermal gradient favors fluid migration and possibly flushes more hydrocarbons.

Where the geothermal gradient is constant, the rate of water expansion increases with depth of burial. Therefore, water expansion becomes increasingly important at depths necessary for the generation of hydrocarbons.

In a geologic model of shale-sandstone interbeds, where the shales have the greater porosity and hence contain a greater volume of water, the expansion resulting from burial would cause water to move out of the shales and into the sandstones. This movement, therefore, could help the migration of hydrocarbons from shales to sandstones.

INTRODUCTION

Sedimentary rocks, especially fine-grained rocks such as shale and siltstone, compact with burial as their pore fluids are expelled. This expulsion may be important in the migration and accumulation of hydrocarbons, in that it probably causes some of the hydrocarbons to move from fine-grained sediments to nearby permeable zones where they finally may be trapped. However, the rate of compaction of fine-grained sediments decreases as they become more deeply buried. In other words, the rate at which the pore fluids are expelled decreases with burial. At subsurface depths where fine-grained source rocks have reached temperatures high enough for hydrocarbon generation, the movement of pore fluids that may contribute to hydrocarbon migration probably is relatively slow.

If fluid expansion occurs at such depths, it might facilitate fluid migration and thus be a favorable factor in the migration of hydrocarbons. In this paper, I suggest that such is the case.

Burst (1969) proposed montmorillonite dehydration as an important factor in moving hydrocarbons at deep subsurface levels; expansion of water associated with a water phase change in the montmorillonite (from interlayer water to free water) is the agent for flushing hydrocarbons from shales. Montmorillonite dehydration seems to occur in a relatively narrow temperature-pressure range.

Water expansion as discussed in this paper is not, however, related to any water phase change. It is continuous as long as the sediments are being buried.

Recently Barker (1972), using a pressure-temperature-density diagram for water, discussed the role of temperature in developing abnormal pressures in the subsurface. He pointed out that, if formation water is isolated and then buried, the water pressure will increase with temperature. The amount of pressure increase can be evaluated by using Barker's diagram. The basic requirement for this type of abnormal pressuring is the physical isolation of the subsurface water.

What will happen if pore water in the sediments is not isolated (or pore pressure is near hydrostatic)? I suggest that the water will expand and contribute to fluid migration.

FLUID MIGRATION DURING CONTINUOUS DEPOSITION AND BURIAL

Figure 1 is a pressure-temperature diagram for water with selected isodensity lines, adapted from Barker (1972). The vertical scale is pressure in psi, and the horizontal scales are temperature in both Centigrade and Fahrenheit. Density values in g/cu cm (and specific volume values in cu cm/g) of water are shown along the isodensity lines. The original data for constructing this diagram were obtained by Kennedy and Holser (1966). Three geothermal-gradient lines of 25°C/km (1.37°F/100 ft), 18°C/km (1°F/100 ft) and 36°C/km (2°F/100 ft)[3] for hydrostatically pressured

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[3] According to Barker (1972), the geothermal gradient in the Louisiana Gulf Coast ranges from 18°C/km to 36°C/km.

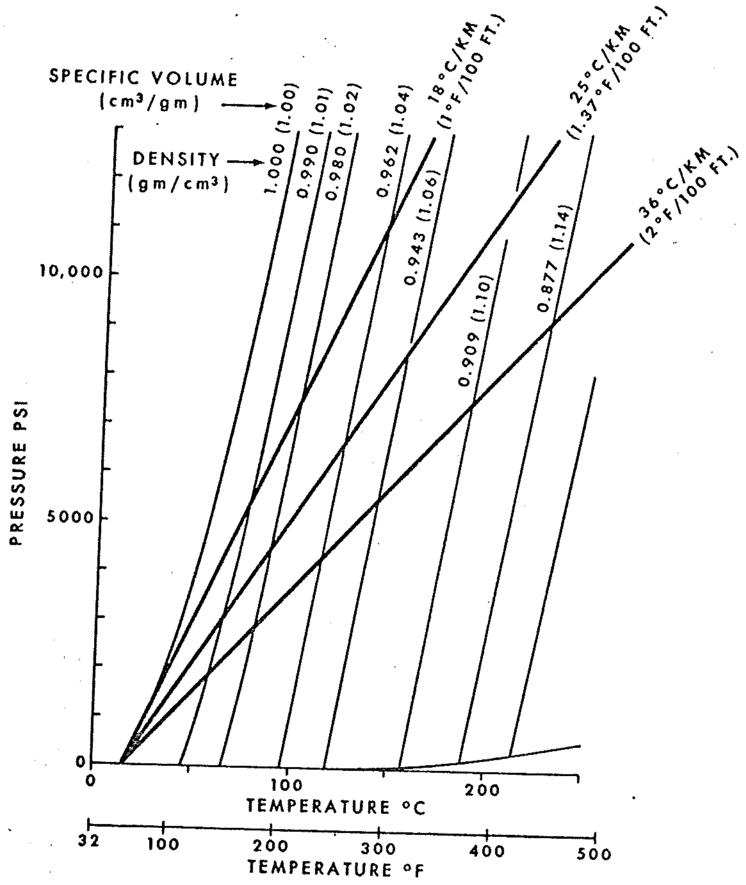


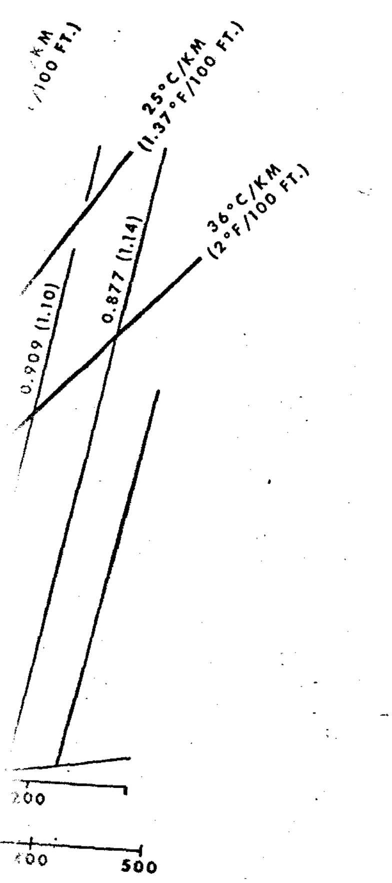
FIG. 1—Pressure-temperature-density (or specific volume) diagram for water. Three geothermal lines of 25°, 18°, and 36°C/km for hydrostatically pressured fluids are superimposed on a basic diagram derived from Barker (1972).

(not isolated) water are superimposed; the lines intercept water isodensity lines whose values decrease as the pressure (or burial depth) increases. A hydrostatic-pressure gradient of 0.47 psi/ft was used. This progression to lower densities and higher specific volumes means that a given weight of water expands with burial; the reason is that the increase of pressure associated with the 0.47 psi/ft hydrostatic gradient is inadequate to hold the water volume constant. Amount of expansion can be derived easily from the specific volume values (cu cm/g), shown in brackets. When the geothermal gradient is 25°C/km (1.37°F/100 ft), for example, the specific volume increases from 1 cu cm/g at 0 psi pressure to 1.10 cu cm/g at 11,600 psi, which corresponds to a burial depth of about 25,000 ft. Thus, a 10-percent water expansion results from about 25,000 ft of burial; this is a significant amount.

Continuous expansion of water for the three geothermal gradients is depicted in Figure 2, where specific volume of water (cu cm/g) is shown on the vertical scale and depth (ft) on the horizontal scale. At 20,000 ft, for example, about 3-percent expansion has occurred for the geothermal gradient of 1°F/100 ft, about 7-percent expansion for 1.37°F/100 ft, and 15 percent for 2°F/100 ft.

Figure 2 shows that rates of increase in specific volume, or rates of expansion, increase with burial depth. This fact is interesting because the *amount* of water expelled by compaction, which is considered to be one of the important agents for hydrocarbon migration, decreases with burial depth, but the subsurface temperature tends to expand water *volume*. This expansion could facilitate fluid migration at depth and hence could favor hydrocarbon migration.

Expansion of rock grains also may be considered in the discussion of fluid migration. The grain expansion would create more intergrain spaces; thus more spaces for water. Its effect, however, is much less significant: the thermal expansion of



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quartz,[4] for example, is only about 1/15 that of water (see Skinner, 1966). In other words, if the ratio of volume of water to that of rock grains is more than about 1:15 (porosity is more than about 6 percent), the effect of water expansion overrides that of grain expansion, resulting in water movement. In the Gulf Coast, a shale porosity of 6 percent would not be attained above 24,000 ft (Dickinson, 1953).

On Figure 1 the geothermal-gradient lines move left as the gradient decreases. A geothermal-gradient line of about 6.5°C/km (0.35°F/100 ft) would parallel the isodensity (isospecific volume) lines; hence there would be no water expansion during burial at this gradient. If the geothermal gradient were less than this value, water would shrink with burial; however, sedimentary basins with such low geothermal gradients are uncommon. Therefore, in most basins water will tend to expand with burial.

A high geothermal gradient resulting in a high subsurface temperature is known to favor the generation of hydrocarbons, especially liquid hydrocarbons (Philippi, 1965). The previous discussion suggests that this factor also favors fluid migration at depths where liquid hydrocarbons could have been generated.

Most hydrocarbon reserves in the Gulf Coast have been found in zones of relatively low pressure gradients (Timko and Fertl, 1971); this implies that fluids in these zones are not isolated. The model described in this paper, therefore, simulates the most prolific zones in the Gulf Coast, and possibly in many other sedimentary basins.

The directions of fluid migration due to water expansion are from a hot place to a cold, from a deep section to a shallow, and from a basin center to its edges. These directions are essentially the same as those of fluid movements caused by shale compaction.

Now, let us assume a geologic model in which sandstone is interbedded with shale. The shale has higher porosity; therefore, if the temperature is increased, water will move from the shale into the sandstone. This movement would favor migration of hydrocarbons from shale into sandstone. Such a model might describe realistically shallow-to-intermediate depth intervals in most sedimentary basins because, at the time of deposition, the shale (or mud) would have had porosities of 70-80 percent, whereas sand had 35-40 percent. Even after a certain amount of compaction during burial, the shale still might have higher porosity.

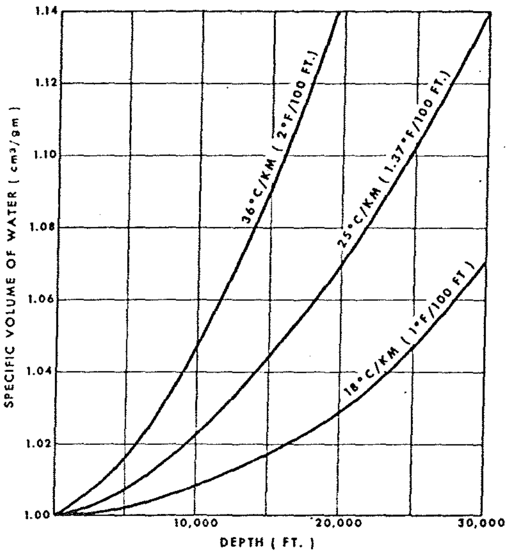

FIG. 2—Specific volume (of water)—depth relations in normally pressured zones for three geothermal gradients of 25°, 18°, and 36°C/km.

In abnormally pressured zones where the pressure is increased by isolation, volume expansion and hence fluid movements are restricted—a condition that does not favor fluid migration.

Fluid Migration during Erosion and Uplift

Erosion and uplift tend to decrease formation temperatures. In areas subjected to these forces, water will tend to shrink in volume and fluids to move in from adjacent unaffected areas. This mechanism might be important in moving hydrocarbons at this stage because during erosion and uplift there is little significant fluid movement from compaction.

Conclusions

1. Most sedimentary basins have geothermal gradients greater than 6.5°C/km (0.35°F/100 ft); in these basins the volumes of water in normal hydrostatic zones tend to increase with burial. This volume increase could facilitate fluid migration at depths where hydrocarbons already have been generated. Therefore, water expansion might be important in moving and accumulating hydrocarbons.
2. Water expansion increases in direct ratio to the geothermal gradient. A high geothermal gradient thus may be a favorable factor for both the generation and the migration of hydrocarbons.
3. The rate of water expansion increases with depth of burial, given a constant geothermal gradient. This fact also favors hydrocarbon migration at relatively great depths.
4. In a model of sand-shale interbeds, expansion

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[4] Thermal expansion of dry clay matrix is not readily available; the value for quartz is used here as the closest approximation.

would cause water to move from the shales into the sandstones, provided the shales have the higher porosities. This movement would favor primary migration.

5. Where erosion and uplift occur, subsurface water tends to shrink in volume and allows fluids from adjacent unaffected areas to move in.

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Time-Temperature Relation in Oil Genesis[1]

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Abstract Chemical kinetic laws for first-order reactions have been applied to the threshold of intense oil generation. If t (in millions of years) represents the age of the threshold formation and T (°K), the corresponding temperature present, t is related to T by the expression $\ln t = 6{,}942 \times 1/T - 14.965$. This equation means that the younger the sedimentary series is, the higher is the temperature of the formation in which the intense oil-genesis phase begins.

INTRODUCTION

In the field of coal geochemistry, several studies have investigated coalification processes. Karweil (1956) found a relation between rank, temperature, and time of coalification. More recently, Lopatin (1971) improved the evaluation of these relations and extended them to disseminated organic matter in sedimentary rocks.

Thermal evolution of sedimentary organic matter depends on temperature, pressure, mineral catalysis, and time. Although the effect of temperature is well established (Philippi, 1965; Louis and Tissot, 1967; Albrecht, 1969), the importance of mineral catalysis seems questionable. Catalytic influence definitely has been demonstrated on pure chemicals but did not appear to be detectable in experiments with kerogen (Hoering and Abelson, 1963). The importance of time has been emphasized by several authors (Vassoyevich *et al.*, 1970; McNab *et al.*, 1952; Teichmüller *et al.*, 1971) and in some cases chemical kinetics have been applied to geochemical data (McNab *et al.*, 1952; Lopatin, 1971; Johns and Shimoyama, 1972; Tissot, 1969).

The present paper deals with the time-temperature relation in oil genesis. Chemical kinetic laws indicate that, to obtain a certain conversion, lower temperatures may be compensated by longer times. Accordingly, an identical effect, *e.g.*, intense oil generation, will be observed in younger series at higher temperatures than in older sediments. The data used for this study are related to the threshold of *intense* oil generation and the time-temperature equivalence has been demonstrated.

CHARACTERIZATION OF THRESHOLD OF INTENSE OIL GENERATION

Philippi (1965), Louis and Tissot (1967), and Albrecht (1969) studied the differences among various yields (organic extract, hydrocarbons, saturates) with burial. They noticed significant increases below a certain depth. This particular depth of burial determined the threshold of *intense* thermal cracking, *i.e.*, the beginning of abundant oil generation (Fig. 1, according to Albrecht, 1969).

The threshold is located in a formation where a certain temperature prevails at present. This tem-

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