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Abstract

Negative gravity anomalies of very local extent and with amplitudes of 1.2 milligals or less have been observed over some known petroleum and natural gas fields in southern California and South Dagestan, U.S.S.R. Field evidence, laboratory measurements, and theory indicate that these anomalies are mainly the result of hydrocarbon pore fluids of densities significantly lower than that of water. Gravity meters already available have the precision necessary to detect some of these anomalies from surface measurements. In addition, a high-precision borehole gravity meter has been developed, by the industrial firm of LaCoste and Romberg, Inc., that can be used in wells with a casing 7 inches or more in diameter and at temperatures below 100°C. Field tests indicate that the prototype attains a precision in wells of ± 0.015 milligal for a single measurement. These observations and the new gravimeter should aid in the search for new petroleum fields and for new reservoirs in known fields that are incompletely explored.

INTRODUCTION

The thinking and interpretation of most users of gravimetric methods of prospecting for petroleum have been dominated by an assumption that positive geologic structures in general produce positive gravity anomalies except where a mineralogically controlled rock-density deficiency (such as arises from mineralogically unusual rocks like salt, gypsum, coal, or diatomite) reverses the general and normal tendency for sedimentary rocks of all types to decrease in porosity and increase in density with greater depth. This assumption is correct for some structures and wholly incorrect for others. Most structural highs that contain volumetrically important reservoirs of petroleum fluids produce gravity anomalies of smaller positive amplitudes than analogous barren structures. This difference is due in part or in whole to the relatively low densities of most petroleum and natural-gas reservoirs. It is found even where no mineralogically controlled rock-density deficiency is present.

Gravity measurements by the writer in 1955 (McCulloh, 1957) in the area of the Salt Lake field, California, and in 1958 in the Santa Fe Springs oil field, California, showed the presence of negative anomalies in those fields, and subsequent investigations indicate that small but recognizable gravity minima that seem to be attributable to the density deficiency resulting from petroleum- or natural gas-saturation are relatively common but have not been widely publicized, and many other minima are probably unrecognized because they are superimposed on larger gravity maxima attributable to pronounced positive structures. Such minima are most noticeable in multiple-zone oil fields of the type prevalent in the deep Tertiary basins of California, characterized by large thicknesses of highly porous petroleum-saturated sandstone. In some extreme cases where total reservoir thickness numbers thousands of feet, where the sandstones are young and highly porous, where petroleum gravity and gas-oil ratios are high, or where reservoir depth is only hundreds or a few thousand feet, conspicuous gravity minima completely unrelated to positive gravity anomalies are produced over pronounced anticlinal culminations. A few examples of such anomalies in California are those of the Santa Fe Springs oil field, the Buena Vista Hills field, and the main producing anticlines of the Midway-Sunset field.

These and related observations led the writer to formulate the hypothesis that such gravity minima are, in important part, the result of hydrocarbon pore fluids of densities significantly lower than that of water, and in 1963 work was begun to test this hypothesis by a critical analysis of the basic factors that control the volumetric and mass properties of sedimentary rocks in situ, and to evaluate the surface and subsurface gravimetric effects expectable from low-density porous reservoir rocks saturated with petroleum fluids. A high-precision borehole gravimeter was recognized as an important tool in testing this hypothesis and in extending its application to the search for deeper and smaller reservoirs than could be detected from surface surveys. Accordingly, the industrial firm of LaCoste and Romberg, Inc. was asked in January 1964 to attempt to modify one of its high-precision sensors to fit a borehole system, the specifications for which were outlined by the writer (McCulloh, 1965a).

Such a gravimeter has now been developed as a modification of the well-known and patented LaCoste and Romberg geodetic gravity meter. A description of the instrument and the results of preliminary field tests are being prepared for publication; one report on mass properties of sedimentary rocks as related to petroleum exploration is being published (McCulloh, 1966) and another is in preparation. Some of the principal conclusions and recommendations are summarized here, however, along with a brief description of the previously published investigations that relate to gravity anomalies associated with petroleum accumulations.

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PREVIOUS WORK

Search of the literature shows that a number of others have observed negative gravity anomalies associated with petroleum accumulations and a few have offered the suggestion that they are the result of petroleum pore fluids.

Miller (1931) was apparently the first to notice and publicly record gravity minima associated with oil-producing anticlines (in California), and he attributed the required deficiency of density to "the compaction and rarefaction of the beds caused by folding." Somewhat later, Poletaev (1934), (not available to the writer but reported by Tsimel'zon, 1959a), independently recognized local gravity minima comparable to those of southern California associated with gas-producing anticlines in South Dagestan, U.S.S.R., and suggested an interpretation "that the rocks saturated with gas have a low density." Barton (1938, p. 377-78; 1944) and Boyd (1946), apparently independently of each other's work, interpreted the prominent gravity minimum over the Lost Hills anticline of the Central Valley of California as a product of excessively low density diatomaceous shales of Miocene age a few hundred to several thousands of feet beneath the surface, even though, in Barton's (1944, p. 13) words, "Simple anticlinal arching of the beds would not seem competent to produce so simple and so sharp an anomaly as the Lost Hills minimum." Tsimel'zon (1956a, 1956b, and 1959a) reexamined the anticlinal gravity minima of South Dagestan first noted by Poletaev and concluded that they result from "zones of fracturing (high porosity)" of carbonate rocks of Cretaceous age in the crests and steep flank parts of the anticlines, a conclusion not greatly unlike that reached by Miller in southern California 25 years earlier. Most recently, Medovskiy and Komarova (1959) examined several Russian anticlinal minima, including those of South Dagestan, in terms of the possible local gravitational effects of the low densities of the petroleum and natural gas filling the pores of the reservoir rocks of these folds. Medovskiy and Komarova (1959, p. 676), concluded: "Thus, these experimental operations allow us to assume that local gravity minima above the crests of structures are caused by gas-oil deposits," a reiteration of the long-buried view attributed to Poletaev (1934). This conclusion, based mainly on a supposed temporal change in gravity indicated by comparison of measurements at a producing pool, using early torsion-balance data and recent gravity meter surveys, was not accepted by Nemtsov (1962), mainly because of the low accuracy of the gravimetric surveys (according to Brod and Vasilev, 1958, Russian gravimetric surveys ordinarily have a maximum precision of only about 0.3 mgl). Nemtsov's (1962) further conclusion that "Amplitudes of model gravitational effects of oil pools in the oil field under consideration ... range from 0.005 to 0.025 mgl, the average being 0.007 to 0.010 mgl" discouraged his hopes regarding gravimeteric identification of such reservoirs, except possible natural gas reservoirs.

PRINCIPAL OBSERVATIONS AND CONCLUSIONS

The results of some field and laboratory studies of mass properties of sedimentary rocks and of the gravimetric effects of petroleum and natural-gas accumulations (McCulloh, 1966) are briefly summarized as follows:

1. Precise and detailed gravimeter surveys show that small local gravity minima are associated with some known shallow to intermediate depth natural reservoirs of petroleum and natural gas (Miller, 1931; Tsimel'zon, 1956a, 1956b, and 1959a). Such gravity minima range in amplitude from more than 1 millagal to values that are scarcely detectable.
2. Under reservoir temperature and pressure, the densities of pure water, brine, and petroleums and natural gases of various compositions vary widely but reveal that a sedimentary rock of any porosity is notably less dense when saturated with petroleum fluid of 30°API gravity, or higher, and a gas-oil ratio of 500 cu ft per bbl, or higher, than when saturated with pure water or brine. For example, the density contrast between rock of 30-percent porosity saturated with water and the same rock saturated with hydrocarbon fluid at a temperature and pressure appropriate to a depth of 4,000 feet ranges from 0.11 g per cm^3 (for petroleum of 30° API gravity and 500 cu ft per bbl gas-oil ratio) to 0.29 g per cm^3 (for pure methane).
3. Consideration of the hypothetical gravimetric effects of well-explored reservoirs indicates that all porous rocks containing low-density petroleum and natural gas produce relatively negative gravity anomalies, but that many such effects are masked or attenuated to the point of concealment. Factors that tend to conceal the negative gravimetric effect of a reservoir are (a) small volume, (b) great depth, (c) low porosity, (d) low petroleum gravity and low gas-oil ratio, (e) high interstitial water content (f) large area-volume ratio, (g) strong density contrasts between other nearby rock masses of large volume, and (h) gravimetric effects of pronounced distortion of isopycnic surfaces outside the reservoir because of very recent deformation of young rocks or very complete consolidation of lithologically heterogeneous rocks of large structural relief, including the positive anomalies associated with some structural highs. Factors that tend to make the nega-

tive gravimetric effects of a reservoir conspicuous are also, in the main, factors which tend to make a reservoir a commercially attractive target. These are (a) large volume, (b) high porosity, (c) shallow depth, (d) high API gravity petroleum, high gas content, or both, (e) large reservoir volume-area ratio, and (f) low interstitial water content. Additional factors that make the negative gravitational effects conspicuous are (a) geologic simplicity in the rocks surrounding the reservoir, (b) negligible to moderate structural relief and distortion of isopycnic surfaces, and (c) thorough consolidation of surrounding nonpetroliferous rocks.

4. While the low densities, characteristic of the hydrocarbon pore fluids of petroleum and natural-gas reservoirs, lower the bulk densities in situ of reservoir rocks sufficiently to account for many of the relatively negative gravimetric effects observed over known oil fields, several other natural factors also tend to produce the same kinds of effects. These factors are not examined per se in this report nor are the observed negative gravimetric effects of known oil fields compared quantitatively with hypothetical effects.

5. Most reservoir rocks are sufficiently dense in spite of the low-density hydrocarbon pore fluids that other, more porous, water-saturated rocks may be equally or even less dense. However, sandstones of the maximum probable or possible porosity at any given depth, those that are in general late Cenozoic in age, possess almost uniquely low densities when saturated with petroleum of 30° API or higher and gas-oil ratio of 500 cu ft per bbl or higher. The nearly unique densities of these rocks are probably sufficient reason in themselves to label the rocks as petroleum bearing if a satisfactory method is available to measure density in boreholes, unless salt, coal, or diatomite are known or suspected constituents, or unless abnormally high aqueous pore-fluid pressure has dilated the rock.

6. Hypothetical subsurface gravimetric effects of well-explored petroleum reservoirs of moderate and small size suggest that most promising extensions of the relatively negative surface gravimetric effects of reservoir rocks can be expected from the application of a borehole gravimeter (or gravity gradiometer) having a sensitivity equal to that of modern surface gravimeters.

7. All the characteristics that tend to cause petroleum and natural-gas reservoirs to possess low densities exist in some degree irrespective of the reservoir's relationship to structure. Reservoirs not associated with prominently positive geologic structures (for example, stratigraphic traps, fracture-porosity traps, reservoirs formed by lateral permeability barriers, fault traps of negligible structural relief, and anticlinal traps of small closure) produce some negative gravity anomalies that may be large enough to be conspicuously identifiable. Reservoirs associated with salt domes or with other structures in which density-deficient rocks are present also produce negative gravimetric effects, but these may be indiscernible or discernible only with difficulty against the background of effects of the other strong density contrasts.

THE BOREHOLE GRAVIMETER

As previously mentioned, the new borehole gravimeter is a modification of the well-known and patented LaCoste and Romberg geodetic gravity meter. It is designed for use in wells with a casing of 7 inches or more in diameter and at temperatures below 100°C. It has been tested to depths of 4150 feet in a Shell Oil Co. well at Santa Fe Springs oil field, California. A single measurement requires only 3 to 5 minutes, and test results indicate that its precision is ±0.015 milligal. With some instrumental refinement and further operating experience, it appears possible to approach closely an ultimate precision in wells of ±0.005 milligal.

Ideally, the precision of a borehole gravimeter should be ±0.001 milligal to permit effective use in the full variety of applications outlined in petroleum exploitation and exploration (McCulloh, 1965a, 1966). The precision of the prototype instrument, however, is sufficient to detect the anomalies expectable from many petroleum accumulations.

Borehole measurement of gravity should prove exceptionally helpful in the evaluation and exploitation of new reservoirs and in the elucidation of many problems of importance to petroleum reservoir engineering (see, for example, McCulloh, 1965b regarding in situ measurement of density and porosity). Moreover, subsurface gravimetric measurements are certain to be of great and novel value in exploring for deeper pools and lateral extensions of known pools in partly explored oil fields, particularly those of the stratigraphic entrapment, fracture-porosity, or unpredictable residual- and solution-porosity types. Lastly, systematic gathering and analysis of subsurface gravimetric data could prove highly beneficial, in conjunction with surface gravity data, in support of any wildcat exploration campaign, but particularly in exploration in basins or regions where much is already known, from previous drilling, about subsurface structural and stratigraphic variations and isopycnic configurations.

Although the focus in the development of the borehole gravimenter has been on petroleum exploration, the instrument should also prove applicable to the search for many other minerals.

RECOMMENDATIONS

The data, observations, and conclusions of the studies referred to in this report lead to several specific recommendations concerning studies applicable to petroleum exploration:

1. Precise gravity maps of many petroliferous regions should be examined, preferably first by suitable trend-surface analyses or graphical or numerical derivative procedures, for evidence of local gravity minima of small amplitude associated with known and explored oil fields in various regions. By this means, an empirical basis could be established for seeking previously unrecognized reservoirs by direct gravimetric detection.

2. Further efforts should be made to calculate from density models of well-explored oil fields their gravimetric effects for comparison with gravity variations actually observed over these fields. By this means, an improved understanding could be reached of factors that control the sizes and shapes of both the small-amplitude and the larger amplitude subsurface gravity anomalies produced by reservoirs of petroleum and natural gas and their surrounding rock masses, and a basis would be established for judging the reliability of such models.

3. Efforts should be continued to improve the sensitivity and accuracy of the borehole gravimeter, reduce its diameter, and extend its temperature (and therefore depth) tolerance.

4. Precise ocean-bottom gravimeter surveys or traverses over seismically or acoustically determined structures should be investigated as a means of predicting, before drilling, the relative productive potential of such structures from their local gravimetric effects. Determination of generalized sub-ocean-bottom structure in water of moderate (and even great) depth has now become comparatively simple and reliable. Analysis of precise gravity measurements made on the ocean bottom over potential trapping structures offers the prospect of greatly reducing exploration risks or greatly enhancing ability to bid wisely in competition over an offshore parcel, the structure of which is moderately well understood.

5. Where known stratigraphic traps and fracture porosity reservoirs are suspected of having unexploited extensions, precise gravity surveys should be conducted to determine the feasibility of locating such suspected extensions by their relatively negative gravimetric effects.

6. Because of their probable future critical importance in investigations of the variations of the underground vertical gradient of gravity, conventional cores from wells already drilled should be carefully conserved.

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