

PARADOXICAL RESISTIVITY ANOMALIES DUE TO SULPHIDES IN SEDIMENTARY ROCKS ASSOCIATED WITH HYDROCARBONS

K. DUCKWORTH¹

Anomalous electrical responses over hydrocarbon reservoirs have been described by Snyder *et al.* (1980) and ascribed by them to an emplacement of finely divided sulphides in the columns of rock above such reservoirs. The mechanism of emplacement of these sulphides was described by Snyder *et al.* as being one of upward migration of fluids from the hydrocarbon. The concept appears to require that these fluids provide a supply of sulphur which combines with metal ions in the sediments above the reservoir to form metallic sulphides. The dominant availability of iron in sedimentary rocks indicates that pyrite would be the sulphide most commonly formed by this process.

Such an emplacement of sulphides would readily generate the complex resistivity anomalies that were described by Snyder (*ibid.*) and it would also account for anomalies that have been reported in transient electrical surveys by Azad (1977), but this concept also has implications for the DC resistivity of rocks, and the present discussion will consider these implications.

The presence of pyrite in hydrocarbon-producing horizons is well known. Examples of this were described in Prudhoe Bay cores by Clavier *et al.* (1976), who reported a range of pyrite content that exceeded 30% by volume in the most heavily mineralized cores. They found that the pyrite in these cores had been formed at the time of deposition of the sediments, so that it possibly predated the emplacement of hydrocarbons. Similar syngenetic pyrite is common in many sediments that contain no hydrocarbon, so that the late diagenetic addition of pyrite to such rocks may not be able to increase their pyrite content significantly. However, in rocks that are barren of syngenetic pyrite, the mechanism proposed by Snyder *et al.* could be significant. The late emplacement of pyrite into sedimentary rocks must cause some of the con-

nate pore fluids to be displaced, and we may expect that this replacement of poorly conductive ionic solutions by highly conductive metallic mineral will lower the over-all DC resistivity of the rocks into which the pyrite is emplaced. However, it must be recognized that emplacement of any metallic sulphide also introduces a highly resistive component into a rock, this being the current-induced polarization resistance at all interfaces between the sulphide and the ionic fluids in the remaining porosity. This interface resistance has been measured for pyrite by Anderson and Keller (1964), Scott and West (1969), Clavier *et al.* (1976), and Klein and Shuey (1978). The work of these authors shows the interface resistance of pyrite to be of the order of $2.5 \times 10^3 \Omega \text{ cm}^2$ for typical electrolyte conditions.

The optimum type of emplacement for maximum interface effect will be one in which the process of emplacement gives rise to the maximum surface area of pyrite by forming separate grains as the process proceeds, rather than that it causes the growth of existing grains. Even if the process is one in which separate grains are continually formed, these grains must coalesce as the volume of sulphide rises. Consequently, the surface area of sulphide exposed to the pore fluids must cease to rise and may even decline, although Pelton *et al.* (1978) found that grain surfaces were preserved even in massive sulphide bodies. Clavier *et al.* (1976) found that interconnected pyrite was present in all the cores they measured as having greater than 7% volume of pyrite. This suggests that the introduced interface resistance will be most significant for pyrite contents less than 5% by volume, and we may anticipate that Snyder's concept would result in pyrite concentrations much lower than 5%.

In experiments with synthetic rock cores in which the metallic content was increased in a

¹Associate Professor, Department of Geology and Geophysics, University of Calgary, Calgary, Alberta

manner that simulated the formation of new, separate mineral grains, McEuen *et al.* (1959) found that, as metallic content was increased from zero to 4% of the solid volume, the resistivity of their synthetic cores increased by approximately 25%. Above 4% of metallic content, the resistivity declined again but did not drop back to the resistivity of the cores containing no metal until 12% by solid volume of metal was reached. In these experiments the metal was not introduced into pre-existing pores as it would be in a natural system and, as a consequence, excess metal had to be used to achieve an effective area of contact between metal and pore fluid. Thus, we may expect that in a natural system much smaller volumes of metallic mineral could achieve these same effects.

This effect of increased resistivity for low-volume fractions of metallic mineral was also reported by Scott and West (1969) for synthetic rock specimens of very high resistivity.

It appears that this effect can be explained as a result of the dominance of the rise of resistance due to surface effects over the reduction of resistance due to the replacement of connate fluid by sulphide. This dominance can occur only at low sulphide volumes, when new grain formation causes surface area to rise significantly without a correspondingly significant replacement of fluids.

A good illustration of the ability of interface resistance to dominate the effect of replacement of fluid by metal was provided by the experiments of Saydam and Duckworth (1978) into the use of thin sheets of stainless steel to simulate polarizable mineral veins. The low-frequency (~ 0.1 Hz) resistivity of a tank of sodium chloride solution rose significantly when thin sheets of stainless steel were introduced into the tank. Simulation of the behaviour of various electrode arrays traversing over an outcropping vein resulted in response profiles that were identical in form and similar in amplitude to theoretical curves published by Van Nostrand and Cook (1966) for perfectly resistive vein-like bodies. Confirmation that this high resistance was a polarized surface effect was provided by repeating the profiles at a frequency of 20 Hz, at which frequency the profiles closely resembled the perfectly conductive vein cases published by Van Nostrand and Cook. A similar dramatic change of interface impedance with increase of frequency was shown by the work of Klein and Shuey (1978), who demonstrated that the surface im-

pedance of pyrite declines by approximately an order of magnitude as frequency increases from 0.001 to 0.5 Hz.

In their investigation of Prudhoe Bay cores, Clavier *et al.* (1976) found that for cores containing less than 5% pyrite the measured porosities, when used in Archie's formula, predicted the measured bulk resistivity of the cores very closely. They interpreted this to mean that the presence of pyrite did not affect the resistivity of those cores. However, an alternative interpretation is possible: that at low-volume fractions of pyrite the surface resistance is dominant, so that the pyrite behaves as just another nonconductive component of the rock. Thus, we may expect that current will flow in the measurable porosity and that Archie's Law will hold. However, the emplacement of that pyrite must have reduced the porosity of those cores, so that in this sense the resistivity of the cores was changed by the pyrite. Thus, the results reported by Clavier *et al.* appear to confirm the resistive nature of a pyrite emplacement of low volume.

We can see that this effect of increased bulk resistivity due to low-volume contents of sulphide suggest that the concept of late emplacement of sulphides into previously barren sediments above a hydrocarbon reservoir could lead to a resistivity contrast between the rocks on and off the reservoir. The initial effect of the emplacement would be to cause a resistivity high over the reservoir. However, given sufficient time, the sulphide content of the sediments might reach a volume at which the lowering of resistivity due to replacement of connate fluid by sulphide would dominate the resistive surface effects and, consequently, produce a resistivity low over the reservoir. Thus, young reservoirs might be identified by high-resistivity columns of sediments above them, while old reservoirs might be accompanied by columns of low-resistivity rocks. We may also infer that, because the concept of an altered column above the reservoir requires that sulphide contents decline as we move off the reservoir, a halo of high resistivity might be found to exist around the low resistivity directly over an old reservoir. If the rocks above a reservoir contain a significant amount of syngenetic sulphides, it becomes more probable that Snyder's concept would lead to a reduction of resistivity over both young and old reservoirs.

If these effects on the bulk resistivity of rocks exist, they will certainly be subtle and will be

superimposed on the wide variety of other influences that may affect resistivity in rocks as measured by surface surveys. Geologic structure, or the high resistivity of the hydrocarbon itself, may readily mask any resistivity effects due to sulphides emplaced above the reservoir. The relative magnitudes of these various effects will vary greatly with geologic setting but, in some settings, the emplacement of sulphides could be the predominant effect.

An additional effect of the concept of fluids ascending from a reservoir is the possibility that those fluids may significantly modify the ionic composition and, consequently, the conductivity of connate pore fluids in the rocks above the reservoir. This would tend to lower the resistivity of those rocks, making it less likely that any resistivity high due to sulphide interface effects could develop. However, the connate fluids in marine sediments will have high ion concentrations, which these ascending fluids may not significantly alter.

A further consequence of the concept of ascending fluids is that their path of ascent could be displaced by any lateral movement of pore fluids in the overlying rocks. The consequent displacement of the sulphide emplacement could lead to electrical anomalies that have no apparent association with a reservoir.

Attempts to use electrical methods to detect oil and gas often treat the problem as one of detecting the electromagnetic effects that originate in the resistive behaviour of the hydrocarbon itself. Examples of this approach have been provided by Kinghorn (1967) and by Eadie and West (1980). If an emplacement of sulphides is present above a hydrocarbon reservoir, it will create strong responses in any system that is attempting to record electromagnetic effects due to the hydrocarbon. In such circumstances it would be necessary to separate the polarization effects of the sulphide and the electromagnetic effects of the hydrocarbon before any useful interpretation of the electromagnetic data could be made. Clearly, the electromagnetic approach would be more successful over reservoirs that have not generated sulphides in the overlying rocks.

Thus it appears that, in the detection of oil and gas, the approach that attempts to locate an anomalous emplacement of sulphides above a reservoir, and the approach that attempts to detect electromagnetic effects direct from the reservoir, are complementary. It will require detailed examination of the geologic setting to

determine which approach will be most successful in any given area. In those geologic settings that appear to favour the existence of sulphide emplacements over the reservoir, recognition of the presence of such sulphides will be provided by either complex resistivity or transient electrical anomalies. However, it can be seen that DC resistivity anomalies also may be detected over such sulphide emplacements and that, in some cases, the sulphides may cause an apparently paradoxical resistivity high.

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