Structural Control of Ground-Water Movement in Miogeosynclinal Rocks of South-Central Nevada

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ABSTRACT

Regional interbasin movement of ground water in highly deformed miogeosynclinal carbonate rocks of the eastern Great Basin has received considerable attention in the literature since 1960. That these regional carbonate aquifer systems — some of which may integrate as many as 13 intermontane basins — are actually compartmentalized by major structural features, has not received adequate emphasis.

In south-central Nevada, major wrench, thrust, and normal faults and folds exert marked control on ground-water movement. Deformation of the carbonate rocks results in regions of high transmissibility, but juxtaposition by faulting or folding of thick clastic strata against carbonate aquifiers results in prominent ground-water barriers, some of which are more than ten miles long. The apparent hydraulic gradients across the thick clastic aquitards vary from 150 to 1300 ft per mile; by contrast gradients in the adjacent carbonate aquifers vary from 0.5 to 10 ft per mile. Barriers may also result from gouge developed along the major fault zones.

Recognition of the structural barriers as well as the conduits is essential for construction of an initial working flow net of a region. In upland areas

the clastic aquitards may exert control on distribution of recharge. Where present in central parts of the flow system, the aquitards act as prominent ground-water dams, and localize minor spring discharge. In discharge areas they localize major spring lines.

Major structures with hydrologic reflections include the Las Vegas Valley shear zone and the Tippinip thrust fault.

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INTRODUCTION

Regional interbasin movement of ground water in the highly deformed miogeosynclinal carbonate rocks of the eastern Great Basin has received considerable attention since 1960, principally by the U.S. Geological Survey. Test drilling at the Nevada Test Site in south-central Nevada has proven that at least five, and probably seven, intermontane basins are hydraulically connected by movement of ground water through the Paleozoic carbonate strata (Winograd, 1962, 1963; Winograd and Eakin, 1964). In east-central Nevada Eakin (1966) has inferred — on the basis of spring discharge and water-level data — that 13 valleys, bordering or near the White River, may constitute a single ground-water basin. In northeastern Nevada, Maxey (1964) has suggested that interbasin movement best explains the uniform discharge of several groups of large springs. The qualitative studies made to date thus indicate that interbasin movement of ground water probably occurs throughout much of the eastern Great Basin. Semiquantitative studies of these complex aquifer systems — either for economic or academic purposes — will depend upon the construction of "working" flow nets of each reservoir. This paper seeks to emphasize, first, that the carbonate aquifers of the miogeosyncline are actually compartmentalized by major structural features which form prominent hydraulic barriers between or within the intermontane basins; and second, that the identification of such structural features, by geologic mapping, is a logical first step for the construction of flow nets for these complex aquifer systems.

At the Nevada Test Site and vicinity, the miogeosynclinal carbonate rocks of Paleozoic age have fracture transmissibilities which range from 1000 to 1,000,000 gpd (gallons per day) per ft, according to pumping test analyses; the transmissibility near the principal discharge area may exceed 5,000,000 gpd per ft, according to regional-flow analysis. The fracture transmissibility of thick clastic rocks of Precambrian, Early Cambrian, Devonian, and Mississippian ages, on the other hand, is extremely low by comparison, less than 1000 gpd per ft, according to hydraulic tests. The best evidence for uniformly low transmissibility of the clastic sequences within the miogeosyncline is the general absence of high-yield springs in these rocks; the spring discharge from the carbonate rocks has been estimated by Eakin (1966) and Maxey (1964) to exceed 200,000 acre-feet annually. Although subjected to the same deformational history as the carbonate strata — and consequently as highly fractured — the clastic rocks are poorly permeable, probably because of their low susceptibility to solution and, in the case of the argillaceous rocks, to their tendency to deform plastically.

Because of their marked difference in transmissibility, it is possible to expect that structural juxtaposition of the clastic and carbonate rocks should result in prominent hydraulic discontinuities. Three examples of such discontinuities are presented (Fig. 1).

EMIGRANT VALLEY

Figure 2 shows part of Emigrant Valley adjacent to the Nevada Test Site. The western half of this valley — the alluvium apron west of Groom Lake playa — is bordered on the east, south, and southwest by Precambrian and Lower Cambrian clastic rocks of the Johnnie, Stirling, Wood Canyon, Zabriskie and Carrara Formations. This outcrop pattern and the regional dip of the clastic and younger Paleozoic carbonate rocks suggest that this part of the valley probably is part of a highly faulted mega-anticline which, prior to block faulting, brought Precambrian and Lower Cambrian clastic rocks to the surface over a wide region. A gravity survey suggests that the bedrock beneath western Emigrant Valley is overlain by as much as 4000 ft of Cenozoic deposits (D. L. Healey and C. H. Miller, written commun., 1965).

Figure 3 is a geologic and hydrologic section through six wells extending from northeastern Yucca Flat to Groom Lake playa. The section is approximately at right angles to the major structural trends. Water levels in three

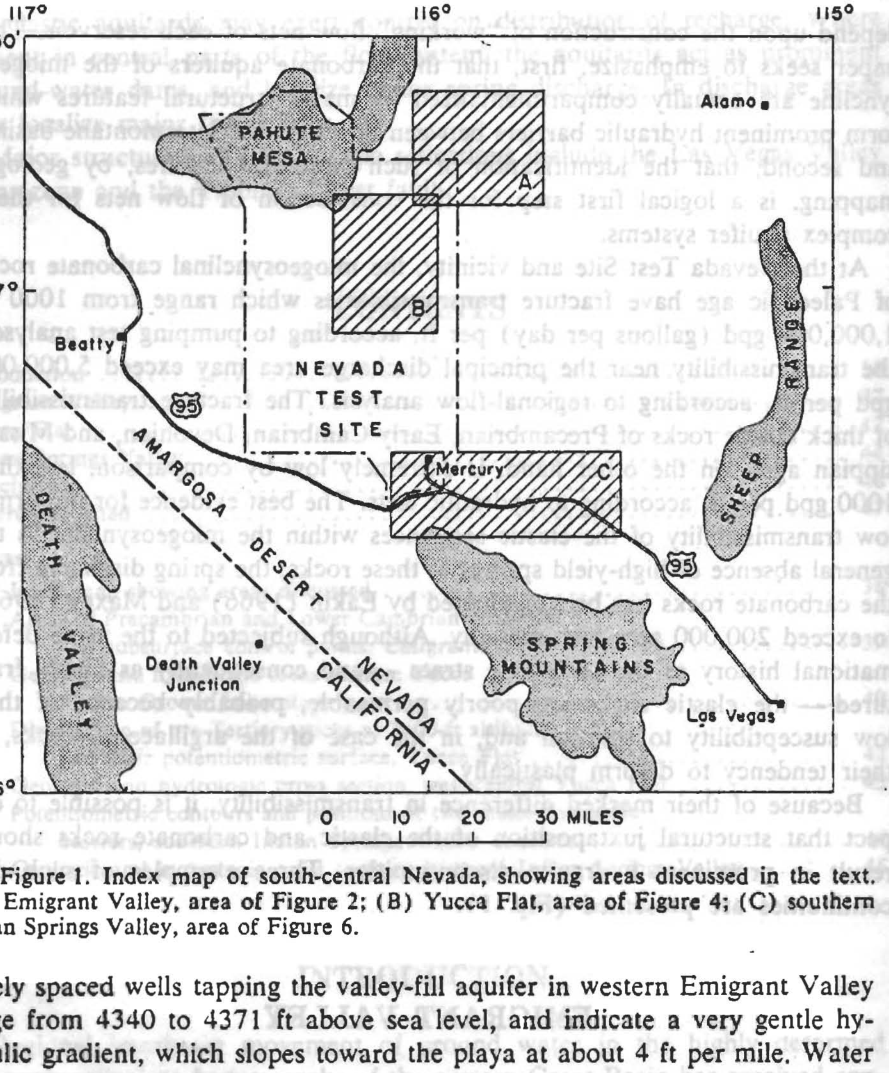

Figure 1. Index map of south-central Nevada, showing areas discussed in the text. (A) Emigrant Valley, area of Figure 2; (B) Yucca Flat, area of Figure 4; (C) southern Indian Springs Valley, area of Figure 6.

widely spaced wells tapping the valley-fill aquifer in western Emigrant Valley range from 4340 to 4371 ft above sea level, and indicate a very gentle hydraulic gradient, which slopes toward the playa at about 4 ft per mile. Water levels in wells tapping older rocks immediately east and west of western Emigrant Valley, however, are considerably lower than the levels within the valley-fill aquifer. The water levels in two wells tapping Tertiary tuff beneath the south border of Groom Lake playa are about 400 to 800 ft lower than the water level in well 4340, 2 miles away along the western border of the playa. (Well numbers on illustrations indicate water-level altitude.) These three wells indicate an apparent eastward hydraulic gradient of 220 to 820 ft per mile. The water level in well 3918 along the northeast border of Yucca Flat is about 450 ft lower than the water level in the valley-fill aquifer of Emigrant Valley; this well taps Precambrian clastic and carbonate rocks. Finally, the water level in well 2413 is about 2000 feet lower than levels in west Emigrant Valley; this well taps carbonate aquifiers, and its potentiometric level (2413 ft altitude) is representative of the carbonate aquifers of Yucca

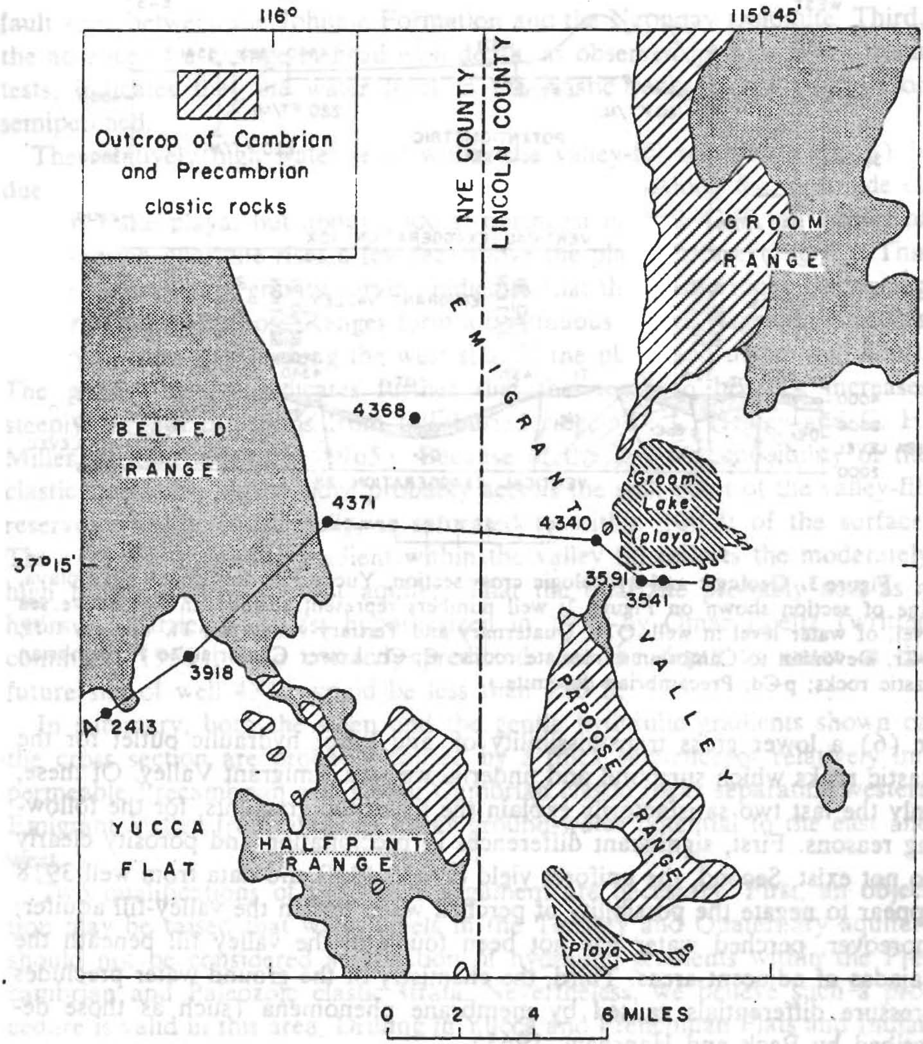

Figure 2. Areas of Precambrian and Lower Cambrian outcrops and subsurface control points, Emigrant Valley. A-B, line of section shown on Figure 3; numbers adjacent to wells represent altitude, in feet above sea level, of water level in well.

Flat. The two wells in Yucca Flat suggest an apparent southwestward gradient — from Emigrant Valley to Yucca Flat — of about 160 to 1300 ft per mile.

The high and relatively flat potentiometric surface in the valley-fill aquifer within western Emigrant Valley and the apparent steep hydraulic gradients developed in the older aquifers in the flanking areas could be due to several causes: (1) markedly greater precipitation on western Emigrant Valley than on the flanking areas; (2) uniform precipitation throughout the region, but the presence of reservoir rocks of considerably lower porosity beneath western Emigrant Valley; (3) the perching of water in the valley-fill aquifer; (4) pressure differentials caused by semipermeable membrane phenomena; (5) a higher discharge outlet for the valley-fill aquifers than for the older aquifers;

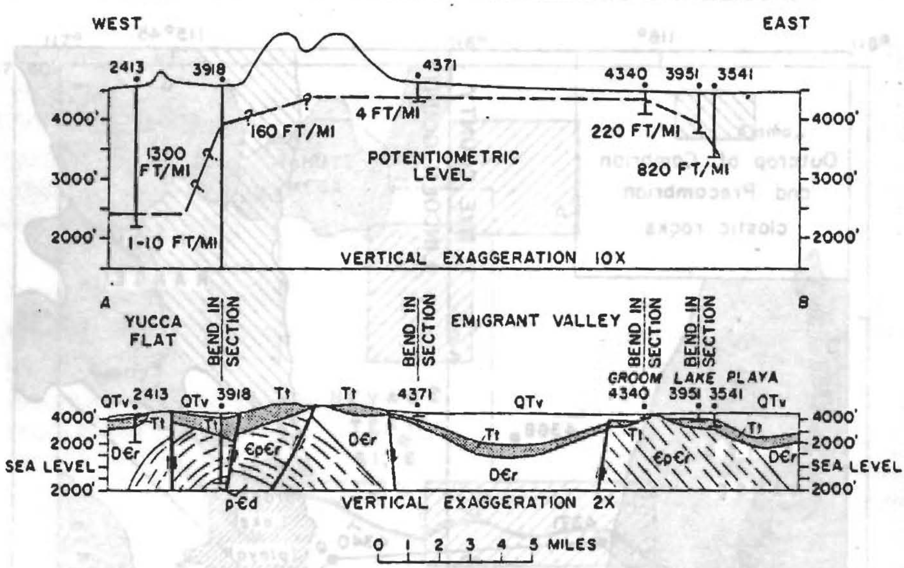

Figure 3. Geologic and hydrologic cross section, Yucca Flat to Groom Lake playa. Line of section shown on Figure 2; well numbers represent altitude, in feet above sea level, of water level in well. QTv, Quaternary and Tertiary valley fill; Tt, Tertiary tuff; D-€r, Devonian to Cambrian carbonate rocks; €p€r, Lower Cambrian to Precambrian clastic rocks; p€d, Precambrian dolomite.)

or (6) a lower gross transmissibility of, and lower hydraulic outlet for the clastic rocks which surround and underlie western Emigrant Valley. Of these, only the last two satisfactorily explain the hydraulic gradients, for the following reasons. First, significant differences in precipitation and porosity clearly do not exist. Second, the uniform yield of well 4340 and data from well 3918 appear to negate the possibility of perched water within the valley-fill aquifer; moreover, perched water has not been found in the valley fill beneath the bajadas of adjacent areas. Third, the chemistry of the ground water precludes pressure differentials caused by membrane phenomena (such as those described by Back and Hanshaw, 1965).

The apparent steep hydraulic gradients on both ends of the cross section (Fig. 3) are believed to reflect the movement of water through the thick clastic aquitards toward points of lower head in Yucca Flat and in eastern Emigrant Valley. The potentiometric surface in both Cenozoic and Paleozoic aquifers in northern and eastern Yucca Flat is well documented and is 2000 ft lower than levels in western Emigrant Valley. The presence of lower levels in eastern Emigrant Valley is not documented by well data, but that part of the valley is underlain chiefly by carbonate rocks, and therefore, the steep eastward gradient probably reflects drainage to lower levels in the carbonate aquifers. Data from well 3918 supports the above interpretation of the steep gradients in three respects. First, its water level gives a control point on the gradient within the clastic rocks. Second, a pumping test of this well shows that the transmissibility of about 4200 ft of Precambrian quartzite, siltstone, and dolomite is less than 600 gpd per ft, and half of this interval reflects a fault zone between the Johnnie Formation and the Noonday Dolomite. Third, the absence of a change in head with depth, as observed in several drill-stem tests, indicates that the water level in the clastic rocks is not perched or semiperched.

The relatively high water level within the valley-fill reservoir (Fig. 3) is due also to the relatively impermeable clastic rocks. Along the west side of Groom Lake playa, but about 1000 ft northeast of well 4340, an outlier of Precambrian quartzite rises a few feet above the playa surface (Fig. 2). This outlier, as well as a gravity survey, indicates that the clastic rocks composing the Groom and Papoose Ranges form a continuous buried ridge which occurs at very shallow depth along the west side of the playa and under well 4340. The gravity survey indicates further that the depth to bedrock increases steeply in both directions from this buried ridge (D. L. Healey and C. H. Miller, written commun., 1965). Because of the low transmissibility of the clastic strata, the buried ridge probably acts as the spill point of the valley-fill reservoir, which, incidentally, is saturated to within 100 ft of the surface. The very low hydraulic gradient within the valley fill reflects the moderately high transmissibility of that aquifer. That the quartzite probably acts as a hydraulic barrier was first hypothesized in 1957 by Omar Loeltz (written commun., 1959), who correctly predicted that the depth to water at the future site of well 4340 would be less than 150 ft.

In summary, both the steep and the gentle hydraulic gradients shown on the cross section are probably caused by a thick sequence of relatively impermeable Precambrian and Lower Cambrian clastic rocks separating western Emigrant Valley from areas of lower ground-water potential to the east and west.

Two qualifications of the above argument are necessary. First, an objection may be raised that water levels in the Tertiary and Quaternary aquifers should not be considered a reflection of hydraulic gradients within the Precambrian and Paleozoic clastic strata. Nevertheless, we believe such a procedure is valid in this area. Drilling in Yucca and Frenchman Flats and Indian Springs Valley, and data in the Amargosa Desert indicate that the water level in the Cenozoic aquifers is usually within 100 ft or less of that in the underlying Paleozoic acquifers or aquitards, except where true perched conditions exist. Because the water-level changes cited are considerably greater than 100 ft, our hypothesis seems valid. In addition, in each area discussed at least one control point is available in the older rocks for confirmation of the above generalization.

The second qualification pertains to the values of hydraulic gradient cited and also values presented in succeeding examples. The hydraulic gradients within the clastic strata may be reasonably continuous, or they may represent discontinuous levels within blocks of rock separated by relatively impermeable faults. For this reason these slopes are referred to as "apparent hydraulic gradients." Whether the gradients are continuous or steplike does not materially change the interpretations presented.

YUCCA FLAT

A second example of the role of the clastic rocks in controlling regional ground-water movement within the miogeosynclinal strata is available from test drilling in Yucca Flat. Figure 4 shows the approximate distribution of carbonate and clastic rocks at 2400 ft altitude, and the potentiometric level for each rock type. The central and east-central part of Yucca Flat is underlain principally by carbonate aquifers, Cambrian through Devonian in age, whereas the western half of the valley contains principally Devonian and Mississipian clastic rocks of the Eleana Formation; the northeastern part of the valley contains Precambrian and Lower Cambrian clastic strata. The Devonian and Mississippian strata are part of the upper plate of the Tippinip thrust fault. In effect, Figure 4 is a crude geologic map of pre-Tertiary rocks at the 2400-ft level, which is about 1500 ft below the floor of Yucca Flat. This level was chosen because the potentiometric surface within the carbonate aquifer ranges from 2380 to only 2415 ft throughout this valley.

The hydraulic gradient in the carbonate aquifer in northern and eastern

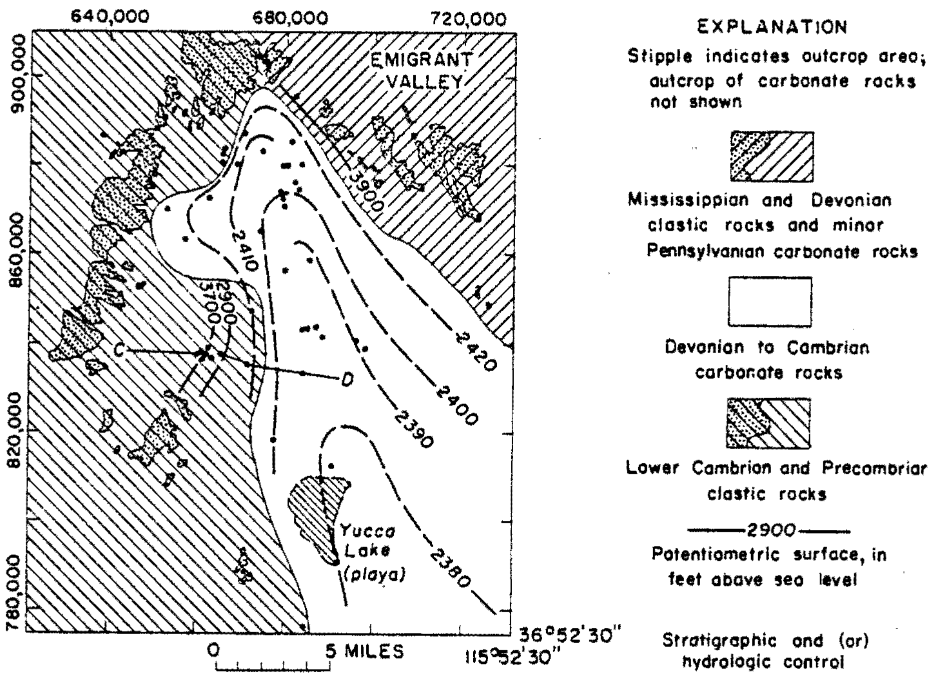

Figure 4. Approximate distribution of pre-Tertiary rocks at 2400-ft altitude and their potentiometric surface, Yucca Flat. Tertiary and Quaternary rocks, which extend below 2400 ft altitude in the central part of the valley, are not shown. The Cambrian through Devonian carbonate aquifers are saturated only below 2420 ft altitude, whereas the Precambrian and Lower Cambrian and Devonian and Mississipian clastic rocks are saturated to altitudes up to and above 3900 ft. The centrally located carbonate wedge thus serves as an hydraulic sink for ground water in the clastic strata. C-D, line of section of Figure 5. 40,000-ft grid based on Nevada State Co-ordinate System (Central Zone).

Yucca Flat generally ranges from one to ten ft per mile. By contrast, the potentiometric level within the clastic rocks of the Eleana Formation ranges from about 2900 to 3800 ft above sea level, with an apparent hydraulic gradient of 240 to 940 ft per mile. Figure 5 is a geologic and hydrologic cross

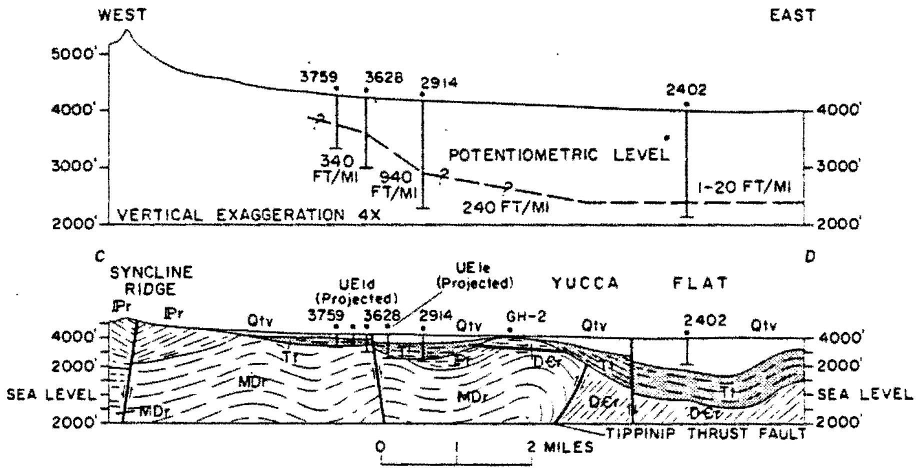

Figure 5. Geologic and hydrologic cross section, west-central Yucca Flat. Line of section shown on Figure 4. QTv, Quaternary and Tertiary valley fill; Tt, Tertiary tuff; IPr, Pennsylvanian carbonate rocks; MDr, Mississippian and Devonian clastic rocks (Eleana Formation); D€r, Devonian to Cambrian carbonate rocks.

section through central Yucca Flat which better illustrates the significant changes in hydraulic gradient within the Eleana Formation. Steep hydraulic gradients also exist within the Precambrian and Lower Cambrian clastic rocks in northeastern Yucca Flat, which was suggested previously by data from well 3918 (Fig. 3). In effect, the carbonate aquifer beneath central and northern Yucca Flat is isolated from carbonate aquifers in adjacent valleys by the bordering clastic aquitards; that is, any ground water moving between basins into the carbonate aquifer would have to pass through — and would consequently be controlled by the transmissibility of — the clastic aquitards. An important distinction exists, however, between the Devonian-Mississippian clastic aquitard which bounds the valley on the west and the Lower Cambrian and Precambrian clastic rocks bordering it on the northeast; namely, in western Yucca Flat the Devonian and Mississippian strata probably are underlain by thousands of feet of lower and middle Paleozoic carbonate aquifers, whereas the clastic strata beneath northeastern Yucca Flat probably are underlain only by the crystalline basement rocks. Thus, the Eleana Formation need not necessarily retard the movement of ground water into Yucca Flat from the west, because such movement might occur through the underlying carbonate aquifers, at depths of several thousand feet. How effective a hydraulic barrier the Eleana Formation is depends on the nature at depth of the Tippinip thrust fault; if the thrust dips steeply for several thousand feet, it could isolate the carbonate strata beneath the central part of the valley from equivalent strata to the west. If it does not, then the ground water in the Eleana Formation may be semiperched above the underlying carbonate rocks.

INDIAN SPRINGS VALLEY

Figure 6 shows the potentiometric contours for both the Quaternary valley fill and Cambrian and Ordovician carbonate aquifers in southern Indian Springs Valley. These contours suggest that two prominent east-trending hydraulic barriers occur between the Nye-Clark County line and Indian Springs, a distance of about 12 miles. The water-level altitude in the valley-fill aquifers south of U.S. Highway 95 is about 3300 ft above sea level, and the level of Indian Springs, which emerges from Pennsylvanian carbonate rocks south of U.S. Highway 95, is about 3175 ft. The shut-in-pressure of this spring, if one could be obtained, would of course, be higher than 3175 ft.

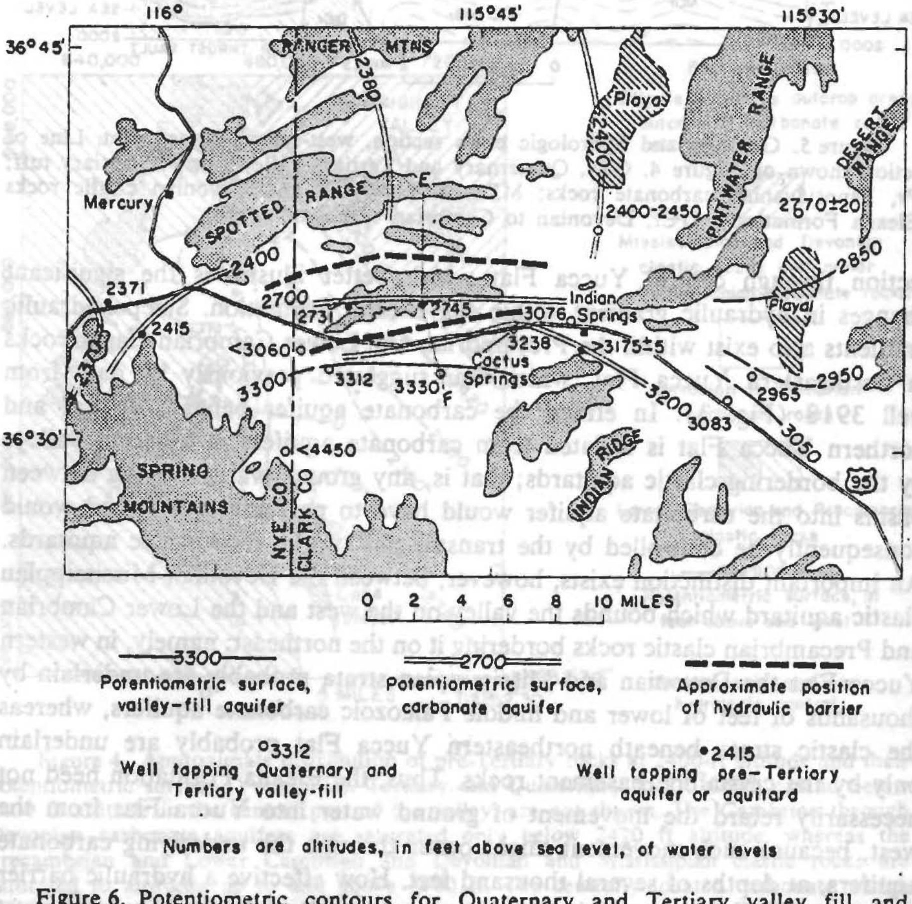

Figure 6. Potentiometric contours for Quaternary and Tertiary valley fill and Cambrian and Ordovician carbonate aquifers, and approximate positions of two major hydraulic barriers, southern Indian Springs Valley. E-F, line of section shown on Figure 7.

The altitude of Cactus Springs, which emerges from valley fill adjacent to U.S. Highway 95 but probably is fed by the shallow underlying carbonate rocks, is about 3240 ft. However, one mile north of U.S. Highway 95 the levels in two test holes tapping Cambrian and Ordovician carbonate rocks are 2731 and 2745 ft altitude. Still farther northward the regional level within the same aquifers is about 2400 ft. The approximate position of the two inferred hydraulic barriers is shown by the broken lines on the illustration.

Figure 7 shows the relation of the hydrology and the geology in a north-south cross section. The position of the southern hydraulic barrier coincides roughly with the inferred position of the Las Vegas Valley shear zone (Longwell, 1960; Longwell and others, 1965; Burchfiel, 1965). There is no evidence to suggest the presence of clastic rocks within the upper part of the zone of saturation adjacent to U.S. Highway 95, and accordingly the hydraulic barrier may be created by gouge developed along the shear zone. The northern barrier, on the other hand, may result from the presence of the Lower Cambrian and older clastic rocks within the zone of saturation north of wells 2745 and 2731.

That the prominent difference in water-level altitude in this area is not due to steep gradients within the carbonate aquifer has been suggested by W. E. Hale of the U.S. Geological Survey on the basis of two facts. First, the water levels in the two wells between the barriers indicate a gentle gradient of 5 ft

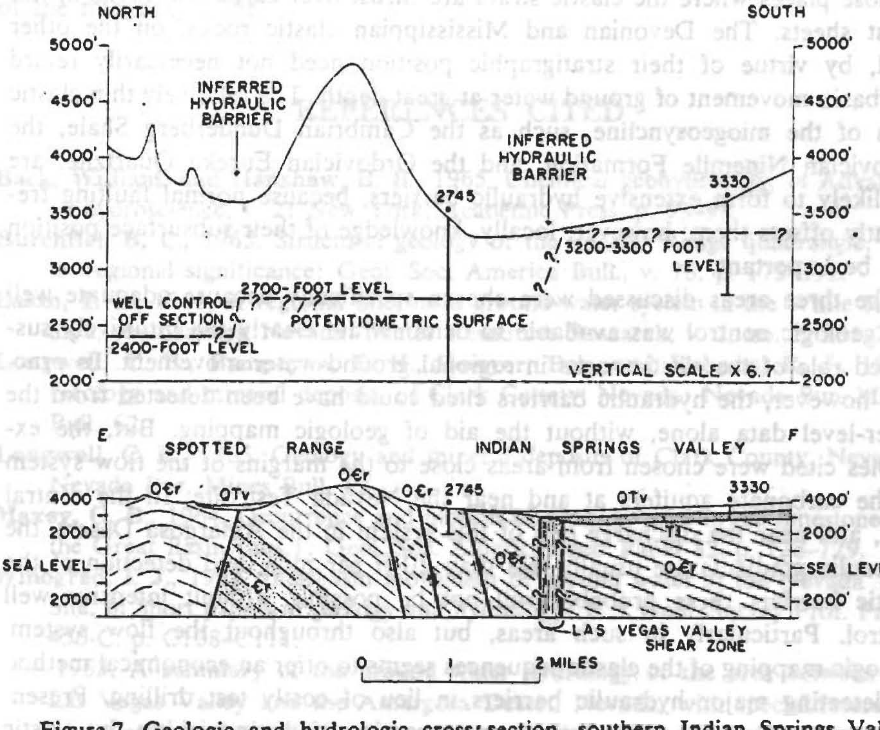

Figure 7. Geologic and hydrologic cross section, southern Indian Springs Valley. Line of section shown on Figure 6. QTv, Quaternary and Tertiary valley fill; Tt, Tertiary tuff; OЄr, Ordovician and Cambrian carbonate rocks; Єr, Lower Cambrian clastic rocks.

per mile to the west. Second, pumping tests of these wells indicate transmissibilities of 10,000 to 20,000 gpd/ft, respectively. It is unlikely that steep hydraulic gradients could develop in such rocks. The carbonate rocks tapped by these wells are, then, part of a relatively permeable block bounded on both north and south by hydraulic barriers, which separate it from other aquifer blocks. It is interesting to note that although the potentiometric contours on Figure 6 suggest a regional northerly movement of water, the principal movement within the carbonate aquifers between the barriers may actually be to the west, as is the regional movement of ground water north of the two barriers.

CONCLUSION

The preceding examples demonstrate how fault blocks containing the thick sequences of clastic rocks of Precambrian, Lower Cambrian, Devonian, and Mississippian age, and perhaps also major shear zones, may compartmentalize or isolate the fault blocks containing the highly permeable carbonate aquifers. The compartmentalization of the aquifer may occur within a single valley or between valleys. From these and several other examples we believe that the Precambrian and Lower Cambrian clastic rocks constitute the hydraulic basement for ground-water movement within the miogeosynclinal strata, except in those places where the clastic strata are thrust over carbonate rocks in flat thrust sheets. The Devonian and Mississippian clastic rocks, on the other hand, by virtue of their stratigraphic position need not necessarily retard interbasin movement of ground water at great depth. The relatively thin clastic units of the miogeosyncline, such as the Cambrian Dunderberg Shale, the Ordovician Ninemile Formation, and the Ordovician Eureka Quartzite, are not likely to form extensive hydraulic barriers, because normal faulting frequently offsets them; however, locally, knowledge of their subsurface position may be important.

The three areas discussed were chosen specifically because adequate well and geologic control was available to demonstrate clearly the intuitively suspected role of the clastic rocks in regional ground-water movement. In practice, however, the hydraulic barriers cited could have been detected from the water-level data alone, without the aid of geologic mapping. But, the examples cited were chosen from areas close to the margins of the flow system in the carbonate aquifers at and near the Nevada Test Site. In the central part, and near the discharge end of this system in the Amargosa Desert, the hydraulic gradients are usually less than 20 ft per mile, and detection of the clastic barriers there probably will not be possible without intensive well control. Particularly in such areas, but also throughout the flow system, geologic mapping of the clastic sequences seems to offer an economical method of detecting major hydraulic barriers in lieu of costly test drilling. Present geophysical methods offer little or no promise of distinguishing the clastic aquitards from the carbonate aquifers at depth.

Recognition of the influence of clastic strata upon movement of ground water in the miogeosynclinal carbonate rocks is important for many purposes. First, and most critical, it may permit the partial assignment of hydraulic boundaries needed for the construction of an initial "working" flow net of an interbasin aquifer system. A flow net, however crude, is essential for academically oriented studies, such as those involving the dating or the geochemistry of ground water, because the major heterogeneities introduced into the flow system by the hydraulic barriers must be carefully considered during selection and evaluation of sampling points. Knowledge of the distribution and extent of the clastic rocks is a prerequisite in a hydrologic analysis of the volume of a reservoir or of the interference between a well field and a prominent spring discharge area. In prospecting for oil within the miogeosyncline, exploration of basins surrounded by clastic strata appears to offer greater potential for entrapment than those groups of basins connected hydraulically by the regional movement of ground water through the carbonate aquifers. Finally, in problems involving radiological safety, drilling of wells for the monitoring of the movement of radionuclides from a reactor site, or from the site of an underground nuclear detonation, clearly requires knowledge of the position of all clastic aquitards, even the relatively thin ones. Geologic study of the areal distribution of the thick clastic rock sequences and major shear zones thus appears to be an important first step for semiquantitative study of the movement of ground water within the complex carbonate aquifers of the miogeosyncline.

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