Geophysical, Geohydrological, and Geochemical Reconnaissance of the Luke Salt Body, Central Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 753

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Preliminary interpretation of a buried salt body in the Basin and Range province of Arizona, based on its gravity field, attendant hydrologic effects, and bromide geochemistry

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GEOPHYSICAL, GEOHYDROLOGICAL, AND GEOCHEMICAL RECONNAISSANCE OF THE LUKE SALT BODY, CENTRAL ARIZONA

By GORDON P. EATON, DONALD L. PETERSON, and HERBERT H. SCHUMANN

ABSTRACT

A major salt body lies hidden beneath the floor of the western Salt River Valley, 17 miles west-northwest of Phoenix, Ariz. It appears to have an arcuate crest and a broad triangular base. Although the salt body was initially interpreted as a structural massif, formed by extensive plastic flow — and that is still the preferred interpretation — the data in hand appear to allow the alternate interpretation that it is an exceedingly thick steep-sided sedimentary prism representing long-lived evaporite deposition in the center of a clastic sedimentary basin. Its crest is marked by several local domes which have bowed and compacted the overlying sedimentary cover, but this phenomenon may be localized and without structural significance for the entire body.

Gravity data suggest that the base of the body is at a depth of at least 6,900 feet, but isolation of that part of the gravity field due to the salt is subjective, and the density stratification of the sediments in the basin is unknown. Thus the interpretation of the gravity data is uncertain. The upper 3,600 feet of the salt has been penetrated by drilling. The body is overlain locally by an anhydrite layer 90 feet thick.

Geohydrologic data indicate that the upper part of the salt has a pronounced local effect on the salinity of the ground water and an indirect effect on the transmissivity of the alluvial fill. Grain-size data suggest that the area above the body stood relatively higher than its surroundings throughout the later part of late Cenozoic time. A local earth-fracture system which appears to owe its location, at least in part, to the existence of the body indicates that adjustments are still occurring, probably in direct response to large ground-water withdrawals.

The salt constituting this body is thought to be of nonmarine origin. Bromine analyses of drill cuttings from the deep test average 2 parts per million, much below the threshold value of 30 parts per million characteristic of marine halite. On the basis of the meager information available from regional geologic studies, we believe that the salt accumulated in a long-standing saline lake sometime during the middle Tertiary, or possibly even earlier.

INTRODUCTION AND ACKNOWLEDGMENTS

In November 1968 Arizona Salt Co. and El Paso Natural Gas Co. drilled an exploratory test hole in the western Salt River Valley, 17 miles west-northwest of Phoenix, Ariz. The hole, 1 mile east of Luke Air Force Base, in sec. 2, T. 2 N., R. 1 W., penetrated the top of an anhydrite section at a depth of 790 feet and passed from anhydrite into halite at a depth of 880 feet. It was continued in halite to a depth of 4,503 feet, at which point drilling was stopped. The presence of a buried salt mass in this area had been suspected from the finding of halite in two water wells (Stulik and Twenter, 1964; Kam and others, 1966) and from the mapping of a large negative gravity anomaly by the U.S. Geological Survey (Peterson, 1965, 1968), according to G. J. Grott (Southwest Salt Co., written commun., 1971).

The drilling of the exploratory well triggered considerable interest in regard to the extent and origin of the salt body, and as a result, the original gravity study was enlarged, and additional geophysical and geochemical data were collected (Eaton and others, 1970, 1971). The conclusion reached as a result of this further study is that the salt mass, here referred to as the Luke salt body, is probably of continental origin. The body includes at least 15 cubic miles of halite. In gross shape it is roughly an irregular, locally domed, ridge-like mass that has an arcuate crest and a broad triangular base. Although its configuration is like that of the core of a large salt anticline, it may represent an undeformed prismatic sedimentary accumulation of salt, only the uppermost part of which has flowed plastically and bowed the overlying alluvial sediments. Similar, or somewhat smaller, volumes of apparently nonmarine halite are known to occur in three other basins to the northwest, and we suggest that appreciable volumes of salt may be found in yet other basins of analogous location along the edge of the plateaus province.

We thank all the people who provided data and materials to us in the course of this study. We are especially grateful to G. J. Grott, of the Southwest Salt Co., who drilled the exploratory hole and who made available the geophysical logs, a set of cuttings, and samples of brines from it. R. J. Hite, of the U.S. Geological Survey, was most helpful to us in suggesting the method of bromine analysis and analyzing the core sample for insolubles. He also acted as a critical sounding board for our evolving ideas on the origin of the Luke salt body.

Our gratitude to M. E. Cooley is apparent from the abundance of references to communications or publications by him. He was most generous in sharing with us his knowledge of regional Tertiary geology and in calling our attention to local occurrences of sodium chloride brines. H. W. Peirce, of the Arizona Bureau of Mines, provided us with the drill cuttings from which the bromine log was prepared and also gave freely of his knowledge of salt as it occurs in Arizona. J. H. Earl, of El Paso Natural Gas Co., provided ideas based on his own investigations of the Luke body. The manuscript benefited significantly from helpful and constructive reviews by M. E. Cooley, E. S. Davidson, R. J. Hite, and W. D. Stanley.

PHYSICAL SETTING AND DELINEATION OF THE SALT BODY

The topography, general geology, and gravity field of the region around the salt body are described and illustrated in this section of the report. Although the basic purpose is to provide a background against which to view some of the characteristics of the body, certain aspects of the setting as related to the probable origin of the body will be discussed briefly.

TOPOGRAPHY

The area in which the Luke salt body occurs is part of the western Salt River Valley, which lies in the northern part of the Basin and Range province of Arizona (fig. 1). The Salt River, from which the valley takes its name, is tributary to the west-flowing Gila River at the south edge of the area. A short distance to the west is the confluence of the Gila and the south-flowing Agua Fria River. The Agua Fria River skirts, and may be deflected slightly by, the crest of the salt body.

The western Salt River Valley is irregularly rimmed by several bedrock ranges, and its gently sloping alluvial floor represents, for the most part, an incised surface that is topographically adjusted to the foot of these ranges in its higher parts and to the through-flowing Salt and Gila Rivers in its lower part (figs. 1, 2). The surface comprises a series of smoothly coalesced alluvial fans and plains through which project isolated steep-flanked bedrock hills. As figure 2 shows, except for the channel of the Agua Fria River and the less pronounced valley of the New River, which joins the Agua Fria from the northeast, the surface is relatively uniform, and the contours swing across the area from west to east in broad arcs open to the south. The only significant interruption of the topography is a pair of low hills west of the Agua Fria River, southeast of Luke Air Force Base. These hills rise above the alluvial surface and are characterized by quasi-radial drainage. Unlike the steep-flanked mountains nearby, the hills are underlain by unconsolidated alluvium. M. E. Cooley, who is widely experienced in the Tertiary geology of Arizona, examined the alluvium exposed in these hills and described it thus (written commun., 1971):

> * * * The deposits comprising the hills * * * are divisible into two units—a younger gravel and an older silt to silty sand. The gravel is thin and is not present on the summits of all the hills. Where it is present, it has the appearance of a terrace deposit, which tends to mask the presence of the underlying unit. The gravel unconformably overlies the older unit and has a maximum observed thickness of 6 feet. It consists mainly of rounded to subrounded pebbles composed of volcanic, granite-gneiss, and other silicic types. In places there are also a few rounded cobbles and small boulders as much as 16 inches in the long dimension. In its overall appearance, the gravel is similar to that transported by the nearby Agua Fria River and dissimilar to the well-rounded to rounded quartzitic and hard silicic pebbly to cobbly gravel exposed in terraces along the Salt River. The imbrication or arrangement of the gravel indicates that it was deposited chiefly by southwestward-moving water, but the range of individual measurements is from southwest, through south, to west-northwest.
>
> The older unit is composed principally of buff silt and some thin layers of silty sand and sand. It is weakly cemented by limy materials. Some thin beds contain more than 75 percent of porous limestone (or caliche). At one exposure, the silt has been crumpled somewhat and is interlaced with very thin calcite veins, which dip at different angles and trend in different directions. In general, the deposit resembles silt-sand beds exposed near the lower Hassayampa River to the west and other fine-grained deposits in Arizona that are considered to be of late Tertiary (chiefly Pliocene) age.

These hills are believed to reflect a doming of the alluvium by the salt because they are near the deep salt test well and, as will be shown later, coincide with a residual-gravity trough that terminates in a gravity minimum east of the well, as well as with an anomaly in ground-water salinity. If Cooley's surmise is correct and if the capping gravel is Quaternary in age but the underlying silt and sand are Pliocene, then stratigraphic evidence for a dome is at hand and supports the topographic interpretation made here.

In order to study the relationship of these hills to the rest of the surface of the western Salt River Valley and, more particularly, to determine their topographic closure in relation to the sloping alluvial plain and the wells which penetrated salt, the topography of the area was digitized on a 2,000-foot grid, and orthogonal polynomial surfaces were fitted to it by digital computer. Figure 3 shows the residual topography obtained by subtracting the fitted fifth-degree polynomial surface from the observed surface. The fifth-degree residual topography was picked for illustration because it tends to minimize the number and amplitude of isolated residuals throughout the area and, at the same time, to enhance the topography of the hills under discussion.

Three features stand out on the residual topographic map: (1) the paired hills southeast of Luke Air Force Base, with closures of about 45 and 55 feet; (2) the channel of the Agua Fria River, with a maximum depth of about 25 feet; and (3) a broad ridge on the east side of the channel, rising about 25 feet above the surrounding alluvial surface.

Two of the three wells (1 and 2 in fig. 3) which penetrated halite in the subsurface are between the +10- and +20-foot contours of residual topography. Well 1, the deep test, penetrated halite at a depth of 880 feet, and well 2, a water well, at a depth of 1,447 feet. No known wells sufficiently deep to penetrate salt have been drilled within the higher parts of the hills, which we regard as marking structural highs on the body.

The phenomenon of circular topographic mounds at the surface above salt domes in the Gulf Coast region has been recognized for many decades. In the section that follows, we present evidence indicating that the area above the Luke salt mass stood topographically high during the latter part of the Neogene.

GEOLOGY

The general geology of the region is illustrated in figure 1. On this map, all igneous and metamorphic rocks, regardless of age, have been lumped together with one pattern. One can easily see by inspection of the map that these rocks, which can be dismissed as a possible source for the salt, make up the vast bulk of all the exposed consolidated rock in the vicinity of Luke Air Force Base.

The closest sedimentary rocks older than late Tertiary in age lie about 20 miles to the east, north of Tempe. They are probably middle Tertiary (Oligocene-early Miocene) in age, according to M. E. Cooley (written commun., 1971), and consist of semiconsolidated arkosic red conglomerates, sandstones, and shales of probable continental origin. Rocks of similar age are exposed about 40 miles to both the northwest and the southwest. Paleozoic and Mesozoic sedimentary rocks (undivided) are exposed 60 miles to the west-northwest of the Luke salt body. About 75 miles north-northeast of the Luke area, in the Verde River Valley, is the Pliocene Verde Formation, which contains known evaporite deposits. These deposits probably are younger than the lower part of the section occupied by the Luke salt body; therefore the Luke salt is probably pre-Pliocene in age. Just northeast of the area shown in figure 1 (130 miles northeast of the Luke body) are the closest known deposits of pre-Tertiary salt. They occur in the marine Supai Formation of Permian and Pennsylvanian age.

We tentatively conclude, on the basis of these observations, that the Luke salt body most likely was not derived from a halite deposit within the local consolidated bedrock of the region. Possibly, Mesozoic and older sedimentary rocks containing evaporites once blanketed the region and were stripped erosionally from the uplifted ranges, but they lie buried in place beneath the floor of the western Salt River Valley; however, this is a speculation without basis in observational fact.

The upper Cenozoic sedimentary deposits of the western Salt River Valley consist of unconsolidated to semiconsolidated gravel, sand, silt, and clay. Locally they contain caliche and thin evaporites, predominantly discontinuous beds of gypsum, in the upper 1,500 feet of the section (Stulik and Twenter, 1964, p. 8). These materials generally occur intermixed in laterally limited beds or lenticular layers. The clastic components, which were derived mainly from the mountainous country to the north and east, probably are Pliocene and Pleistocene, but at depths exceeding 1,500 to 2,000 feet they may be Miocene or older. Sedimentary rocks of middle Tertiary age are known to underlie upper Tertiary deposits at Gila Bend and in areas northeast of Phoenix and west of Casa Grande. According to M. E. Cooley (written commun., 1971), the Pliocene-Pleistocene deposits in the deeper parts of many of the basins in this region (the area shown in fig. 1) are generally less than 2,000 feet thick, and in some basins, such as at Gila Bend, they are only 1,000 to 1,200 feet thick.

Data from the three wells penetrating the salt body suggest that the upper part occurs through a range of stratigraphic levels. The locations of the exploratory well (1) and the two water wells (2 and 3) that penetrated halite are shown in figure 3. Well 2 penetrated 5 feet of "solid rock salt" and bottomed therein at a depth of 1,452 feet, after passing through 1,447 feet of mixed clay, sand, conglomerate, and gypsum, with clay predominating (Kam and others, 1966, p. 50). Well 3 penetrated halite and associated brines at a depth of about 2,320 to 2,350 feet (Stulik and Twenter, 1964, p. 11). The section overlying the salt in this well consists of clay, silt, sand, and gravel, with clay and silt predominating. The total depth is not on record. The data from all three of these wells were used in modeling the salt mass.

Cenozoic deposits seem at present to be the most

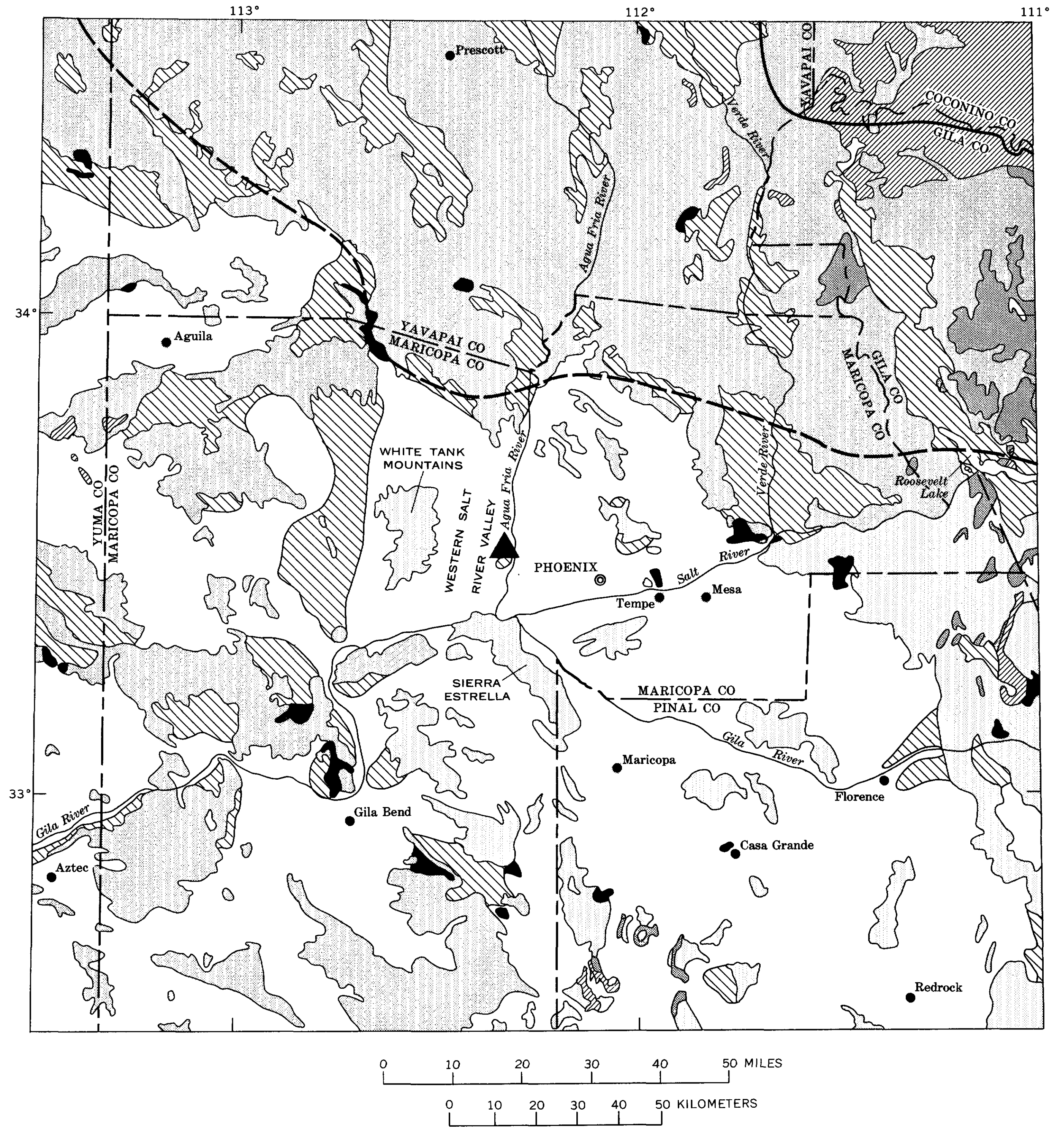


FIGURE 1. — Index map of central Arizona, showing general geology of region around western Salt River Valley (generalized from Wilson and others, 1969, with modifications from Cooley, 1967, and M. E. Cooley, written commun., 1971). Note the general scarcity of lower Cenozoic and older sedimentary rocks throughout the region. The heavy solid line in the northeast corner of the map marks the Mogollon Rim, at the southern edge of the Colorado Plateaus. South of the heavy dashed line is the Basin and Range province. The region between these lines is transitional. The area of the present investigation is bounded by the White Tank Mountains on the west, the Sierra Estrella on the south, the city of Phoenix on the east, and the northern border of the Basin and Range province on the north.

EXPLANATION

Mainly Quaternary deposits

Mainly upper Tertiary (Pliocene) deposits

Middle Tertiary sedimentary rocks

Mesozoic and Paleozoic sedimentary rocks

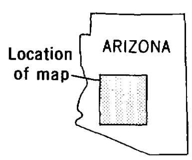
Precambrian sedimentary rocks; slightly metamorphosed

Phanerozoic and Precambrian intrusive, extrusive, and metamorphic rocks

Contact

Location of Luke salt body

Physiographic province boundaries



likely enclosing rocks for the Luke salt body. A possible precedence for determining such an occurrence is found in Hualpai and Detrital Valleys, 170 miles to the northwest, in extreme northwestern Arizona (Pierce and Rich, 1962; Peirce, 1969). There, 500 to more than 1,190 feet of salt, apparently within the Pliocene Muddy Creek Formation, of continental origin, was tapped by drilling. In Virgin Valley, Nev., immediately north-northwest of that, an exploratory drill hole passed through 1,700 feet of halite enclosed by the Muddy Creek Formation without penetrating the base of the body (Mannion, 1963, p. 171–173).

The only published description of the alluvium near Luke Air Force Base is that of Stulik and Twenter (1964). Because the layers constituting the valley fill are lenticular, these investigators digitized available well logs (mainly drillers' logs) in terms of weighted percentages of fine-grained materials and prepared two maps which they used in a qualitative interpretation of geohydrologic parameters. One of these maps (their pl. 2) is reproduced here in modified form as figure 4.[1] It illustrates, in a general way, the gross grain-size variations in the upper 200 to 500 feet of valley fill. The area southeast of Luke Air Force Base is underlain by a high proportion (more than 60 percent) of fine-grained sediments. Surrounding this area, in moatlike fashion, are areas of coarse-grained sediments (less than 60 percent fines) that were probably deposited by major streams. The axes of discontinuous areas with less than 40 percent fines are shown in figure 4 by light dashed lines. Two interpretations based on this map are possible for the area east and south of Luke Air Force Base: (1) this area stood relatively high throughout the period of deposition (middle to late Quaternary?) represented by the interval sampled, or (2) the finer grained materials are older (Pliocene to early Pleistocene?) sediments lifted, during the late Quaternary, to a higher structural level by doming. In the first interpretation, the high would have deflected the major streams around it in a subannular fashion, thereby producing the facies pattern observed. Such drainage patterns are observed commonly around salt domes (Thornbury, 1969, p. 214–216). In the second interpretation, the fine-grained and the surrounding coarse-grained materials are not different facies of the same stratigraphic unit, but are of different ages. Although we prefer the first interpretation, there is no firm basis for choosing between them. The relative altitude of this tract today is attributed to continual arching of the topographic surface by the rising salt.

The facies variations noted here probably have tended to reduce the topographic closure or relief over the salt, because the finest grained (and therefore most compactible) sediments occur directly above the salt body, and the coarser grained, less compactible sediments are distributed in the surrounding area. The net effect of differential compaction would be to reduce the height of the domed surface relative to the surrounding terrain. Thus the residual topography shown in figure 3 may reflect a minimum value for the doming of the topographic surface relative to the rise of the salt beneath it.

GEOPHYSICS

The geophysical setting of the Luke salt body is known almost entirely from gravity data, although

[1]Although Stulik and Twenter digitized each log in units of 20 percent, we question whether the data have real significance in increments this small. In part, a driller's descriptive term is based on how the material drills, rather than on its lithology. We have therefore broken their detailed map down into only two units, separated by their 60-percent contour line.

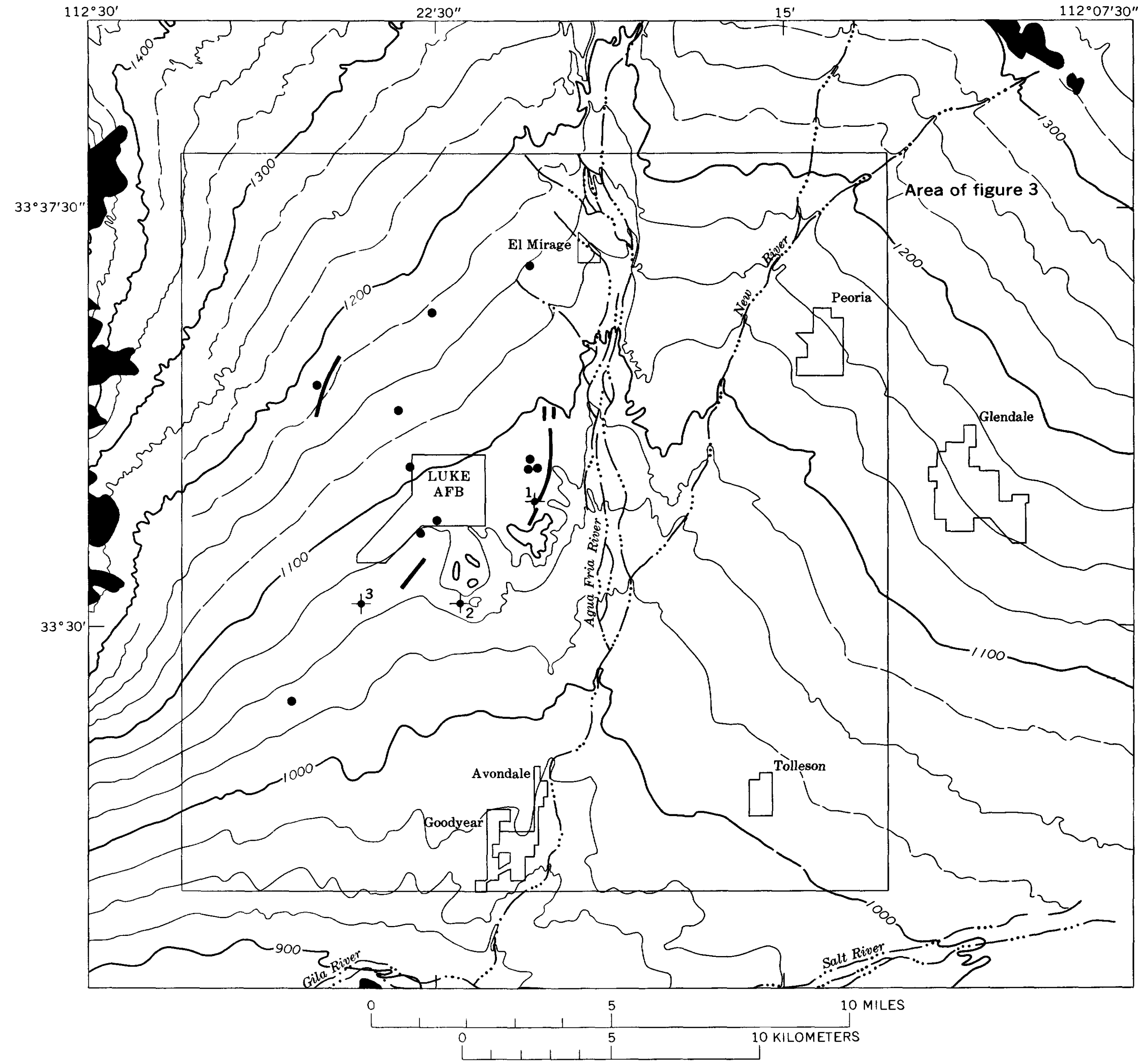


FIGURE 2. — Topography of western Salt River Valley (from the following U.S. Geological Survey 7 ½-minute quadrangle maps: Calderwood Butte, 1957; El Mirage, 1957; Fowler, 1952; Glendale, 1957; Hedgpeth Hills, 1957; McMicken Dam, 1957; Perryville, 1957; Tolleson, 1957; and Waddell, 1957). Contour interval is 25 feet; dashed contour lines interpolated from maps with 10-foot contour interval. Note hilly area southeast of Luke Air Force Base. Bedrock outcrops are shown in solid black near margins of map. Short heavy lines represent open fractures in alluvium or offsets of paved surfaces; solid dots indicate wells with crushed or collapsed casings, as indicated by Kam, Schumann, Kister, and Arteaga (1966). Wells 1, 2, and 3 represent wells that penetrated halite.

a limited amount of reconnaissance aeromagnetic data have been gathered also, in the hope that they might provide an independent means of determining the depth to the crystalline basement. Unfortunately, no aeromagnetic anomalies suitable for this purpose were recorded in the general area of the salt body.

Figure 5 is a Bouguer gravity map of the western Salt River Valley based on the earlier work of Peterson (1965) and on 118 supplementary measurements made in the course of the present study. The principal features shown on the map are (1) a large gravity low, with a northwest-trending axis between

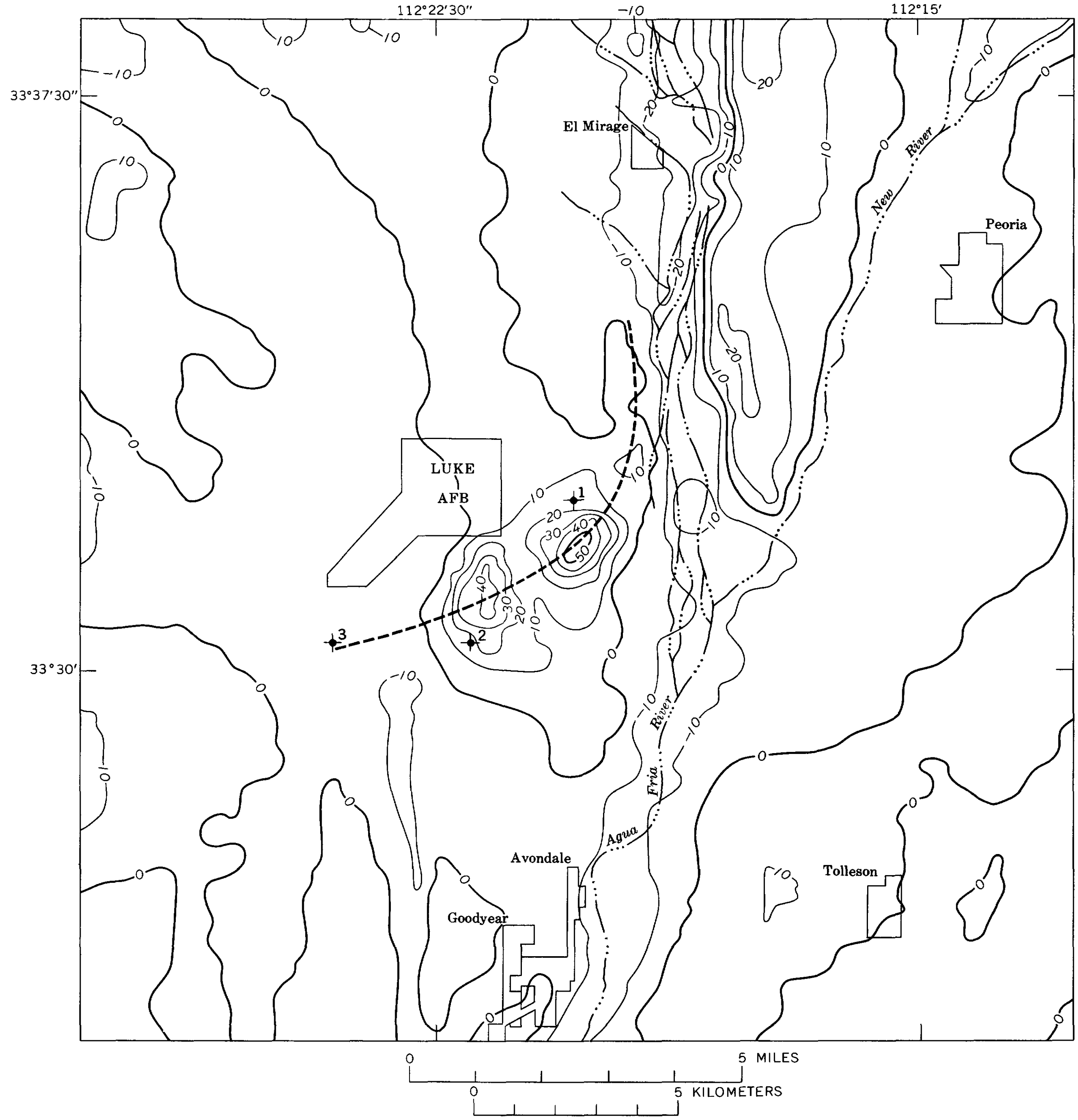


FIGURE 3. — Fifth-degree residual topography of the Luke area. Computer-generated map derived by subtracting a fitted fifth-degree polynomial surface from a digitized topographic map of the area. Contour interval is 10 feet. Solid dots with ticks represent wells that penetrated massive evaporites. Dashed line is axis of that part of salt body above a depth of 2,500 feet, as shown in figure 12.

Luke Air Force Base and El Mirage, parallel to the regional structural grain; (2) steep gradients flanking the east, south, and west sides of this low; and (3) a sinuous gravity high trending northwest and north on the east side of Glendale and Peoria. Most of the major gravity low is due to the presence of a thick sedimentary fill of moderate density. The sinuous high probably reflects a broad ridge of relatively dense bedrock buried at shallow depth. The steep flanking gradients of the low are thought to reflect zones of high-angle normal faulting bounding the grabenlike basin in which the fill accumulated.

Of particular interest here are the details of the central part of the gravity low. Irregularities in the

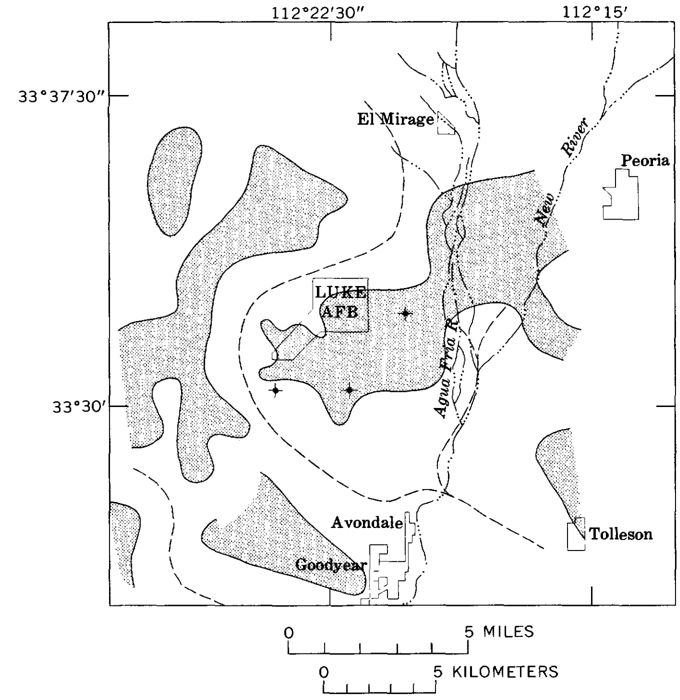


FIGURE 4. — Areas of predominantly fine-grained sediments more than 700 feet above sea level in the stratigraphic section of the western Salt River Valley (modified from Stulik and Twenter, 1964, pl. 2). Shading indicates areas where the valley fill contains more than 60-percent clay and silt, and local thin beds or streaks of gypsum. Light dashed lines are the axes of areas of coarse-grained material. Note subannular pattern of these axes about an area centered southeast of Luke Air Force Base. Solid dots with ticks represent wells that penetrated massive halite.

−90-mgal (milligal) and lower contours seem to define a subtle, local gravity closure, the axis of which trends northeast to north at a moderate angle across the axis of the large low. Notable is the pronounced reentrant (defined by the relatively sharp convexity of contours toward the southwest) caused by this local feature, on the south side of Luke Air Force Base. The gradients of the local closure are steeper than those of the regional low *in the axial region of the latter*, allowing the possibility, but not proving, that the source of the local closure is at a relatively shallow depth.

Crude estimates of the maximum depth to bedrock beneath the major low, based on density contrasts between valley-fill sediments and bedrock appropriate for this part of the Basin and Range province, *and ignoring the presence of the salt*, place the basement[2] surface at a depth between 10,000 and 15,000 feet. This range of approximate depths derived from the gravity data is in approximate accord with a depth of roughly 11,000 feet derived from a reconnaissance seismic reflection measurement (J. H. Earl, oral commun., 1970).

[2]The term "basement" is used here in the geophysical sense. It refers to relatively dense, well-consolidated rocks of any composition or age underlying the weakly consolidated to unconsolidated valley fill.

The observation of a local gravity closure with a relatively shallow source suggests the presence of an anomalous body within the valley fill. This body produces a gravity minimum, which indicates that the structure has a bulk density less than that of the valley fill. This evidence, together with the observation that wells 1, 2, and 3 bottomed in halite, suggests that the peculiarities in the center of the principal low are related to a large mass of halite. If a local residual anomaly could be isolated by appropriate means, the gravity data could be used to determine the approximate size and shape of this salt mass. Such an isolation is attempted with the aid of other data (figs. 3, 4, 6, 7, and 8), and some of these data are presented next to help define the horizontal extent of the upper several hundred feet of the salt body.

GEOHYDROLOGIC DATA BEARING ON THE OCCURRENCE OF THE SALT

Because of rapid urbanization and agricultural and industrial development in the Phoenix area, an abundance of well data is available for the area. Three relatively recent studies by the U.S. Geological Survey (Stulik and Twenter, 1964; Kam and others, 1966; Anderson, 1968) provide adequate detail in the area of interest for the delineation of specific anomalies, each of which appears to relate to the salt mass.

Stulik and Twenter (1964) noted the occurrence of unusually high salinity in five wells on the east and south sides of Luke Air Force Base. Noted also was the local occurrence of conspicuous earth fractures and collapsed or crushed well casings, believed to be associated with recent land subsidence induced by large-scale ground-water withdrawal.

Kam, Schumann, Kister, and Arteaga (1966) presented several maps and tables that likewise indicate unusual geohydrologic conditions in the vicinity of the base. Data selected from these two reports are presented here, and figure 7 was taken directly from the study by Anderson (1968).

SALINITY OF THE GROUND WATER

In order to study geographic variations in groundwater salinity to see if they relate to the salt mass under study, we tabulated specific-conductance data from available sources (Stulik and Twenter, 1964, table 4; Kam and others, 1966, tables 3 and 4) and converted the values to total dissolved solids. Specific conductance was chosen as the principal indicator of salinity because data in this form were available for many more wells than were analyses of total dissolved solids.

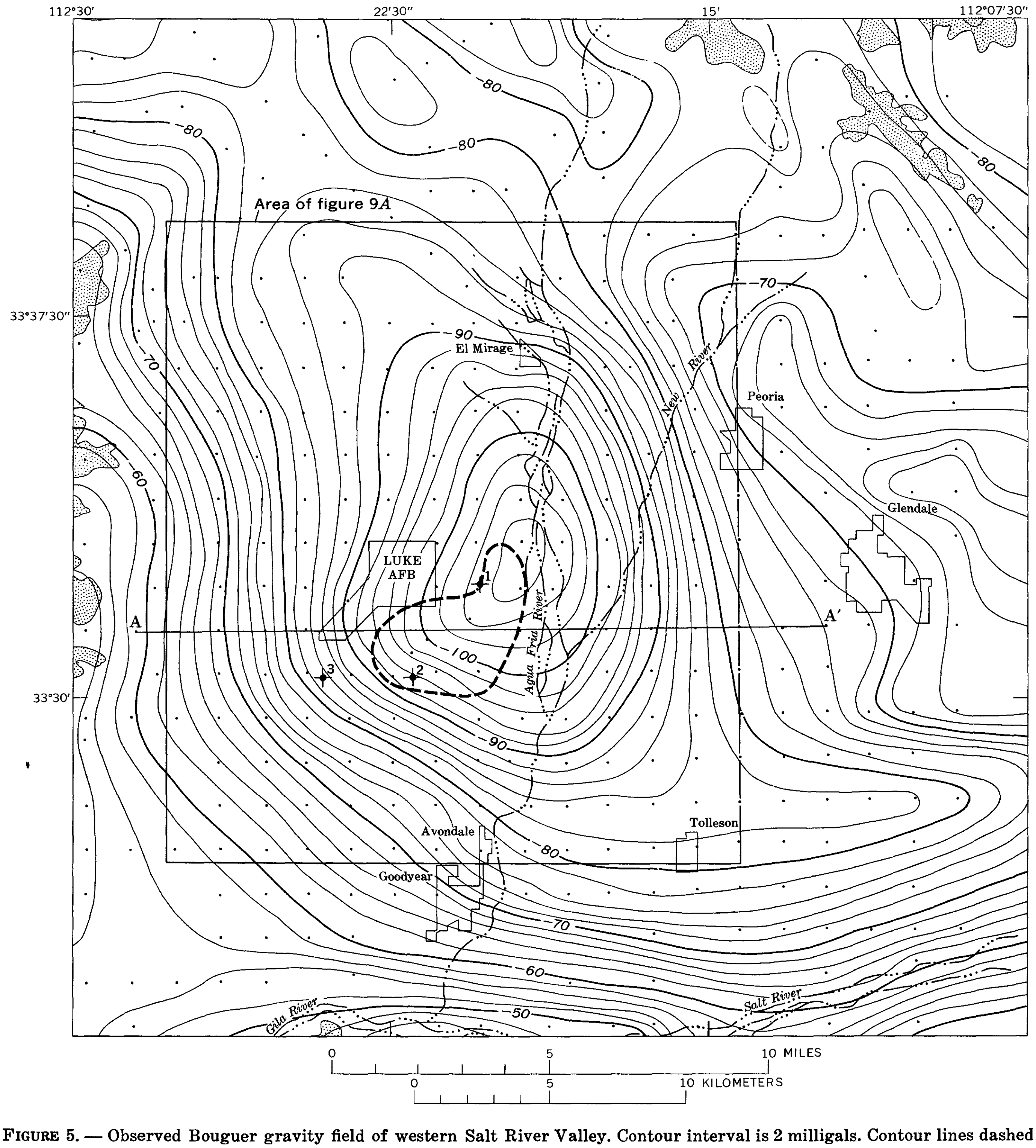


FIGURE 5. — Observed Bouguer gravity field of western Salt River Valley. Contour interval is 2 milligals. Contour lines dashed in areas of sparse control. Small dots are gravity stations. Large solid dots with ticks represent the three wells which penetrated massive halite. Heavy dashed line is approximate edge of top of salt body based on data in figures 3, 4, 6, 7, and 8. Profile *A–A'* is shown in figure 9*B* and illustrates the derivation of residual gravity values used in modeling the salt mass. Stippled pattern represents exposed bedrock.

As is well known, there is a linear relation between dissolved-solids concentration and specific conductance in simple dilute solutions of a single salt (Hem, 1959, p. 40). Approximate values of dissolved solids were computed by multiplying the observed specific conductance values by 0.60. This factor was determined empirically for the Luke area from pairs of measurements of both parameters. Water quality data are available from only one of the three wells that penetrated the salt body. This well (well 3 in fig. 6) was sampled at various intervals, including one near the top of the evaporite sequence. The value for this well in figure 6 represents an average of values for waters from a zone 175 to 250 feet above the halite. The composited value, 5,300 mg/l (milligrams per liter) reflects very clearly the effect of the salt on ground-water composition.

The areal distribution of computed dissolved-solids content is shown in figure 6. Ground water in the northern and northwestern parts of the area contains less than 500 mg/l of total dissolved solids. In the southern part of the area, near the Salt and Gila Rivers, the ground water contains more than 3,000 mg/l of dissolved solids.

A large anomaly, shown by the crosshatching, with salinity values ranging from 500 to more than 9,000 mg/l dissolved solids, exists south and east of Luke Air Force Base and reflects the presence of the salt mass. It is in the same general area as that of anomalous topography (fig. 3) and fine-grained valley-fill sediments (fig. 4). It also includes the three wells that penetrated halite.

The dissolved-solids data should be viewed only as a qualitative indicator of the salt mass. Water sampled at each well represents a composite of waters from different depths and stratigraphic zones penetrated by the wells, and the wells themselves range greatly in depth (from 100 to more than 1,000 ft). After being backfilled or plugged to shallower depths, some of the deeper wells that had produced water containing large amounts of dissolved solids were found to produce less saline water (Stulik and Twenter, 1964, p. 26).

TRANSMISSIVITY OF THE VALLEY-FILL SEDIMENTS

Anderson (1968) presented a map of the transmissivity of the sediments in this region, and the relevant part of this map is reproduced here as figure 7. It shows a local area of low transmissivity existing southeast of Luke Air Force Base and extending northward along the course of the Agua Fria River. Comparison of this figure with figure 4 indicates a rough correlation between areas of fine-grained alluvium and areas of relatively low transmissivity, even though the grain-size data represent, at most, the upper 500 feet of the valley fill, whereas the transmissivities represent the upper 1,000 to 1,200 feet.

Stulik and Twenter (1964) commented on the relationship between the area of low permeability (or transmissivity) east and south of Luke Air Force Base and the high proportion of fine-grained materials in the same area. In our opinion, however, an additional factor may have influenced the distribution of transmissivities—namely, the local reduction of pore volume in the valley-fill sediments, due to compaction caused by the buoyant rise of salt beneath the sediments and (or) by differential compaction over the crest of the salt. Such a reduction in porosity would serve further to reduce the permeability of the sediments. Alternatively, if the area of fine-grained sediments represents upbowed, older valley-fill sediments, the reduced permeability may be a function of a greater degree of cementation.

Interestingly, in conjunction with this hypothesis of compaction-reduced transmissivity, a concentration of wells with a history of casing collapse and several open earth fissures occurs in the area (fig. 7). Although both phenomena, generally attributed to dewatering of the valley fill, are also observed north and northwest of Luke Air Force Base, their relative concentration in the area of the base suggests a localized concentration of stress giving rise to horizontal extension and vertical compression. Such a stress field is to be expected from a doming of the alluvium by the rising salt.

DEEP-WELL DATA

All the wells within a 7.5-mile radius of the discovery well with total depths of, or exceeding, 1,000 feet are located in figure 8. Most of the wells that did not penetrate appreciable evaporites (shown as open circles in fig. 8) probably should be regarded only as fixing upper limits for the top of the salt body, for conceivably they may terminate only a few tens of feet above the body. At least one of them, however, sharply limits the horizontal extent of the uppermost part of the body. The well with a total depth of 1,055 feet, immediately adjacent to the discovery well (1), evidently was drilled just off the upper flank of the salt mass, for although it did not encounter halite, it did produce saline water, and dried cuttings of clastic sediments showed light salt incrustation. Similarly, the well with a total depth of 1,605 feet, 2 miles southeast of the southeast corner of Luke Air Force Base, probably bottoms not far above the southeast-sloping southern flank of the body. These well data aid in further delineating the probable area of the upper part of the salt and provide a guide that was used in examining gravity profiles for apparent expressions of the salt.

Subtle details of the Bouguer gravity map (fig. 5), which, as noted earlier, can be interpreted as reflecting the presence of a salt massif, are here used in an attempt to define the approximate shape of the massif. Additional observations on topography

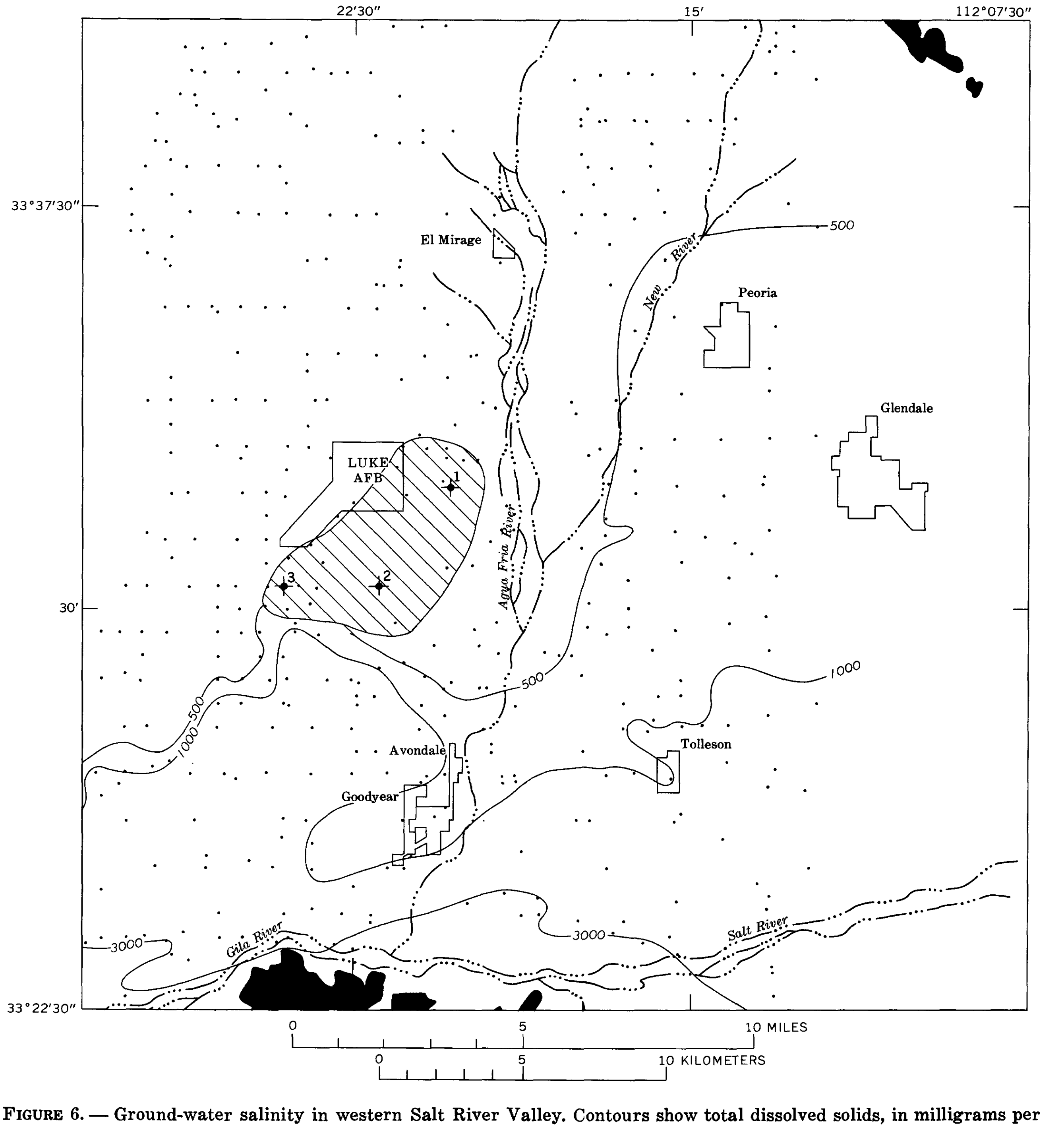


FIGURE 6. — Ground-water salinity in western Salt River Valley. Contours show total dissolved solids, in milligrams per liter. Small dots are wells whose salinity values were used in preparation of the map. Crosshatching indicates area of brackish to saline water ranging erratically in salinity from 500 to more than 9,000 mg/l. Large dots with ticks show location of the three wells that penetrated halite. Solid pattern represents areas of exposed bedrock.

(fig. 3), variations in salinity of the ground water (fig. 6), and lithofacies variations in the alluvial sediments of the valley (fig. 4) all serve to delineate the upper part of the salt mass. Pertinent features of figures 3, 4, 6, and 7 roughly define the eastern and southern edges of the salt body. Further definition of the body is provided by two of the three wells that penetrated salt and by other relatively deep wells in the vicinity that did not. The general extent of the upper part of the salt body, as based on these data, is shown in figure 5 by a heavy dashed line. Note that well 3, where salt was not penetrated

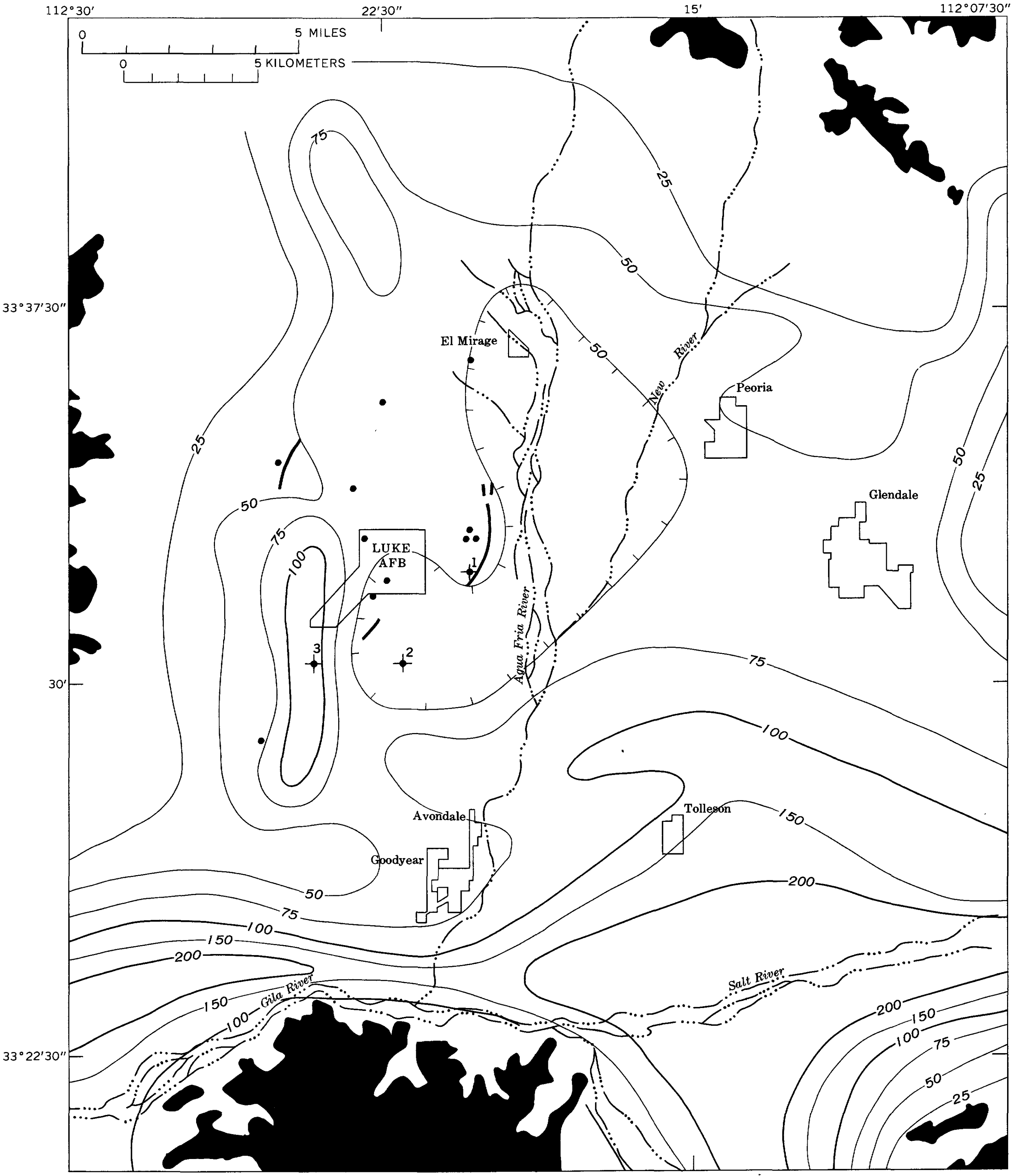
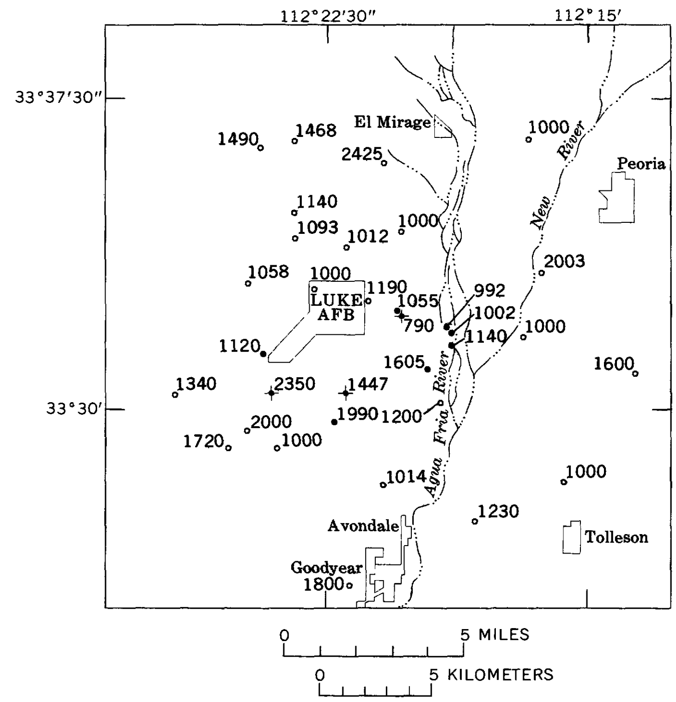


FIGURE 7. — Transmissivity of valley-fill sediments of western Salt River Valley. (Modified from Anderson, 1968, pl. 2.) Contours indicate transmissivity, in thousands of gallons per day per foot, of the upper 1,000 to 1,200 feet of the section. Solid pattern represents areas of exposed bedrock. Note area of reduced transmissivity (<50) south and east of Luke Air Force Base and concentration of collapsed wells (solid dots) and earth fissures (heavy lines) on the west side of the area of low transmissivity. Contour interval is 25,000 or 50,000 gallons per day per foot.



EXPLANATION

1447

Well which penetrated upper part of evaporite body
Number is depth, in feet, at which top was encountered

1490

Deep well which did not encounter appreciable evaporites
Number is total depth, in feet, of well

1120

Well used as constraint in gravity modeling
Number is total depth, in feet, of well

FIGURE 8. — Distribution of deep wells within 7.5-mile radius of center of crest of the Luke salt body.

until a depth of 2,320 to 2,350 feet was reached, falls outside this line. Thus the dashed line defines only the upper 1,000 feet or so of the salt body.

GRAVITY DATA

CALCULATION OF RESIDUAL GRAVITY

After the areal extent of the upper part of the salt body had been roughly defined, it was feasible to attempt a separation of the observed Bouguer gravity field (fig. 5) into its individual components. Three sources were considered: (1) Density contrasts within or below the crystalline basement, (2) the density contrast at the alluvium-basement interface, producing an anomaly associated with the thick prism of alluvium in the western Salt River Valley, and (3) the density contrast between the alluvium and the enclosed salt.

The problem of separation is not amenable to an exact solution because of the ambiguity inherent in the interpretation of potential field data. We do know, however, that the three gravitational sources cited above occur at successively shallower depths, in the order listed. Also, experience gained from gravity surveys elsewhere indicates that gravity fields associated with simple, symmetrical grabens can be closely approximated by polynomial surfaces of low degree.

Because the approximate location and plan of the upper part of the salt mass had been deduced from geologic and hydrogeologic information, we decided to attempt direct derivation of a residual, the source of which could be easily modeled. The principal difficulty in this effort was that the salt occurs within the area of closure of the anomaly associated with the prism of valley-fill sediments. Thus, we were seeking to define a closure (due to the salt) superimposed on another closure (due to the alluvial valley fill) of like algebraic sign. Although the approximate location of the first closure was known, its amplitude was not. In order to estimate the amplitude to a first approximation, we subjected the gravity data to two calculations. In the first, which was done to remove regional crustal or subcrustal effects, a gravity field with low curvature was derived by contouring gravity data for all those stations on bedrock in an area of 3,300 square miles. The data for this were taken from Peterson (1965). The resulting field was subtracted from the observed field, producing a first-step residual supposedly free of effects due to variations in density beneath the basement surface.

In the second calculation, the first-step residual, assumed to contain components associated with both the valley-fill sediments and the salt enclosed within them, was fitted with a second-degree polynomial surface. This surface was assumed to approximate the gravity field associated with the fill alone, and on this assumption rests the accuracy of the derived model. The algebraic difference between the fitted polynomial surface and the first-step residual yields a second-step residual theoretically reflecting the effect of the salt alone. This second-step residual is shown in figure 9*A*. The closure of the negative anomaly due to the salt is approximately 12 mgal. Surrounding it are areas of discrete positive anomalies with amplitudes of 6 to 8 mgal. The gradients of these positive anomalies are gentler than those of the low associated with the salt and are believed to be due either to broad topographic irregularities on the buried bedrock surface or to lithologic variations within the upper part of the basement. Maximum depth to the source of these positive anomalies, calculated by the method of Bott and Smith (1958), ranges from 10,000 to 12,000 feet.

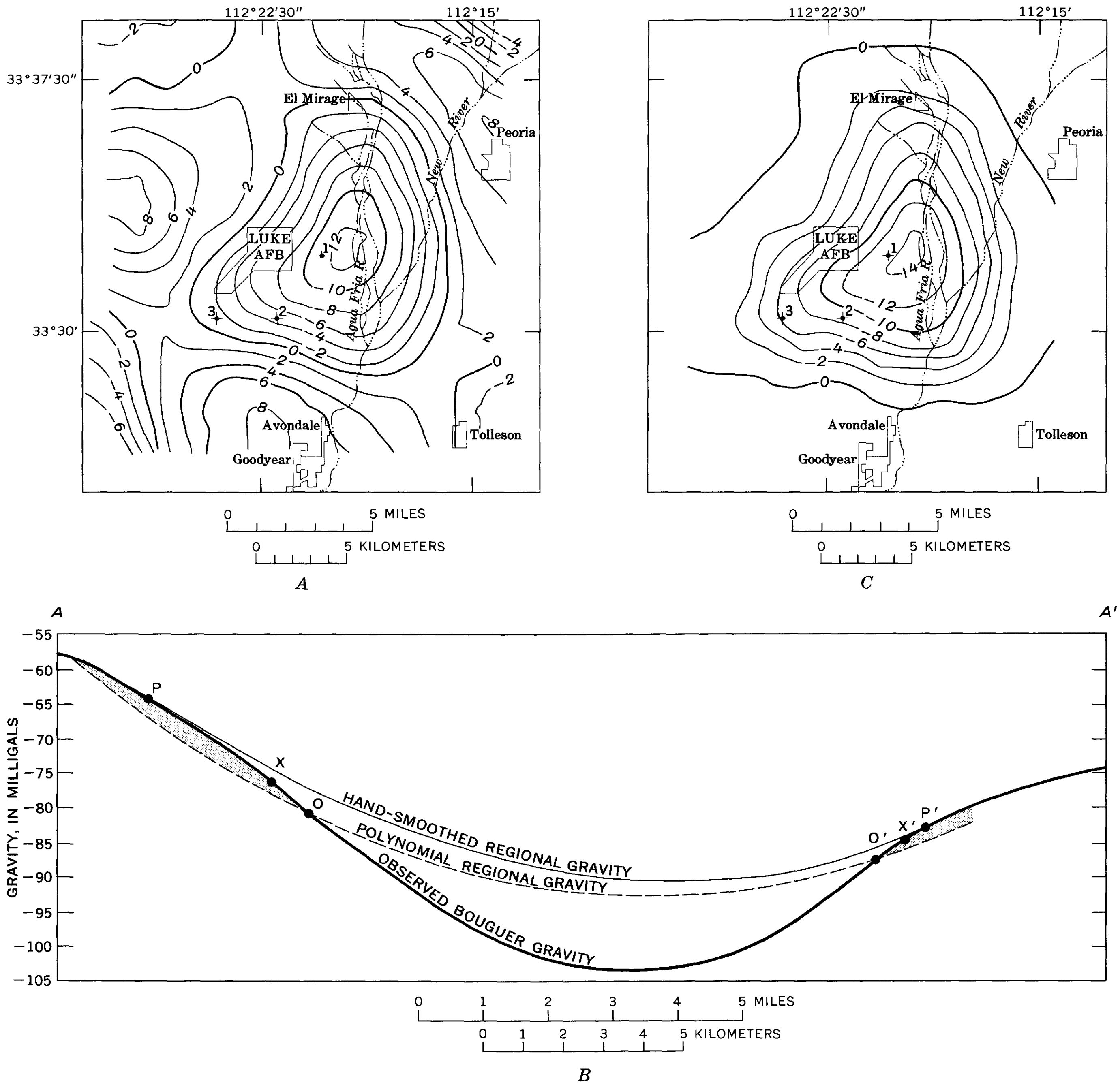


FIGURE 9. — Residual Bouguer gravity associated with the Luke salt body. Contour interval 2 mgal. *A*, Computer-generated map of second-degree polynomial residual gravity. *B*, Profile *A–A'* (see fig. 5 for location) shows observed Bouguer gravity field in relation to both the polynomial "regional"[1] field, used in deriving map *A*, and the hand-smoothed "regional"[2] field, used in deriving map *C*. Shaded areas represent, in part, the positive residual anomalies in *A*. P and P', points at which hand-smoothed regional profile approaches observed profile; O and O', points of zero value on computer-generated polynomial residual field; X and X', breaks in slope. *C*, Residual-gravity map prepared from orthogonal grid of hand-smoothed profiles. Wells 1, 2, and 3 are those which penetrated the salt body.

[1]Use of the term "regional" here refers to a field which consists of the gravitational effect of the valley fill, as opposed to the more normal usage of the term "regional" in referring to the effects of deep crustal and subcrustal sources only.

[2]Use of the term "regional" here refers to a field that consists of the gravitational effect of both the valley-fill sediments and the deep crustal and subcrustal sources.

The amplitudes of all the residual anomalies shown in figure 9*A* are in part a function of the method of fitting the polynomial surface. Skeels (1967) discussed and illustrated the deleterious effect of including with the data to be fitted by such a surface those points specifically related to the residual anomaly one is attempting to isolate. In the present instance, we had little alternative but to include them, because figure 5 shows that those parts of the gravity field outside the −84-mgal contour are too irregular to be approximated as a whole by a second-degree surface. Because of this, we decided to restrict the area to be fitted to that part that we judged by inspection to be amenable to the fitting of a surface of low degree—namely, that part within the rectangle shown (fig. 5). Unfortunately, much of this restricted area was suspected of including effects of the residual anomaly we wished to isolate. The rationale for proceeding in the face of this difficulty was that the results were to be regarded only as a first approximation. All the data within the rectangle, including those directly over the top of the salt, were incorporated in computing the polynomial surface. The effect was to give the resulting surface a slightly sharper curvature than it would have had otherwise and, as a result, to lead to a minimum value for the residual anomaly associated with the salt and a maximum value for positive anomalies bordering the residual low. For a simple, two-dimensional illustration of this effect, see figure 9*B* or Skeels (1967, figs. 1 and 2).

The computer-generated, second-step polynomial residual map (fig. 9*A*) was used as a guide in the creation of another residual map prepared from a grid of profiles smoothed by inspection. These profiles were drawn through the field data points shown in figure 5, and each profile was smoothed with reference to its counterpart profile of the polynomial "regional" surface, which had produced a minimum value for the closure of the residual anomaly related to the salt. The points at which the hand-smoothed "regional" profiles approached the observed profiles (for example, P and P′ in fig. 9*B*) were made to lie outside the points of zero value (O and O′) on the polynomial "regional" surface. Subtle breaks in slope (for example, X and X′) were observed on both flanks of most, but not all, profiles at the anticipated locations, and the "regional" curves were bridged smoothly across the observed profiles between these points. Pairs of "regional" values from intersecting profiles were then adjusted to bring them into mutual agreement. The final values were subtracted from the values of observed Bouguer gravity at each field station, and the results were contoured to produce figure 9*C*.

As anticipated, there is a gross similarity between the residual maps of figures 9*A* and 9*C*. However, figure 9*C* differs in the magnitude of its closure, the curvature of the residual surface, the location of the zero contour, and the absence of satellite positive anomalies. We regard the residual map (fig. 9*C*) prepared from the grid of profiles as the more accurate representation of the residual anomaly associated with the salt. Local irregularities are undoubtedly a function of the rather arbitrary method of drawing the smooth "regional" profiles.

INTERPRETATION OF RESIDUAL GRAVITY

The residual anomaly shown in figure 9*C* was used to derive a total of 14 models of the salt mass, of which about five or six were refined to the point of matching the residual field rather closely. Depth control for the top of the body was provided by the three wells that penetrated the salt and the seven that did not (fig. 8). We knew nothing of the depth, extent, or configuration of the base of the body, and in the process of modeling we made the simple assumption that the base was both horizontal and planar. Any discrepancies between the configuration of the actual body and the configurations of the derived gravity models which stem from the wrongness of this assumption are probably larger than those due to other sources, because of the relative insensitivity of the gravity method to density variations at a level about as deep as that of the probable base of the salt.

The residual-gravity map (fig. 9*C*) probably is in error in significant ways because of the rather arbitrary assumptions made in preparing it. Because the closure of the gravity anomaly due to the salt coincides in part with the closure due to the valley fill, as noted above, the residual map may contain elements that properly belong to the gravity field due to the clastic sedimentary prism of the western Salt River Valley. In particular, the northern and southeastern apices of the crude triangles defined by the residual gravity contour lines might reflect cross-fault-controlled wedging out of the trough of alluvial sediments against a basement surface rising steeply both to the north and to the southeast from a central deep east of Luke Air Force Base. The "regional" map used in the preparation of the residual map (fig. 9*C*) reflects a nonfaulted gentle wedging out of the alluvial prism, but the ability to discriminate the effects of the two sources fades where the basement surface rises to levels comparable to those occupied by the salt.

Another source of error in our models relates to the occurrence of the anhydrite penetrated in drilling the exploration well. (See lithologic log in fig. 10.)

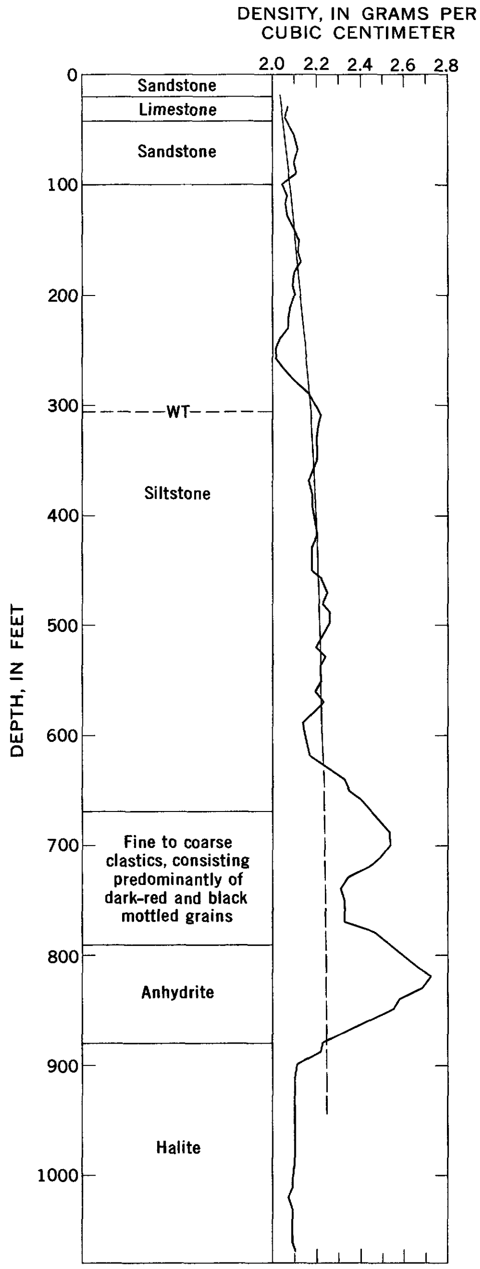


FIGURE 10. — Density and generalized lithology of upper 1,100 feet of deep well penetrating salt body (well 1 in figs. 2, 3, 5, 6, 7, 9, and 12). Irregular curve represents five-point moving average of a gamma-gamma density log digitized at 10-foot intervals. Smooth curve with dashed lower part is idealized depth-density function fitted to the data by inspection and employed in gravity modeling. Light dashed line labeled "WT" on lithologic log represents position of the water table at time of logging.

The anhydrite presents a problem in interpreting the residual gravity, for it is not continuous over the entire top of the structure and, because it was not penetrated in either well 2 or 3, its lateral extent is unknown. Therefore the anhydrite layer, which is denser than any of the other rocks in the area, was ignored in modeling.

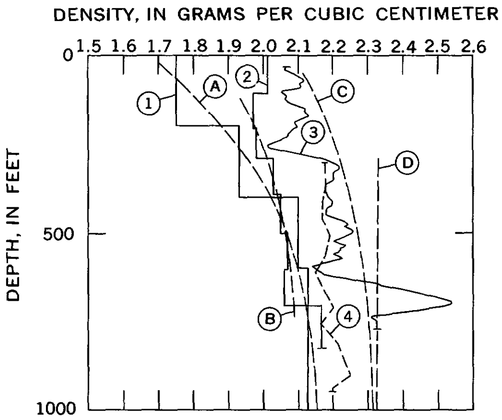
In addition to the uncertainty posed by the anhydrite, we have few data bearing on the density of the alluvium and, therefore, on the density contrast between alluvium and salt, which is of the utmost importance in gravity modeling.

Each of the uncertainties cited above is sufficiently great that the final results should be regarded as only one of many possible schematic approximations of the shape and extent of the salt body. Certainly our models should not be regarded as a guide to further drilling, and they provide only a rough estimate of the total reserves of halite.

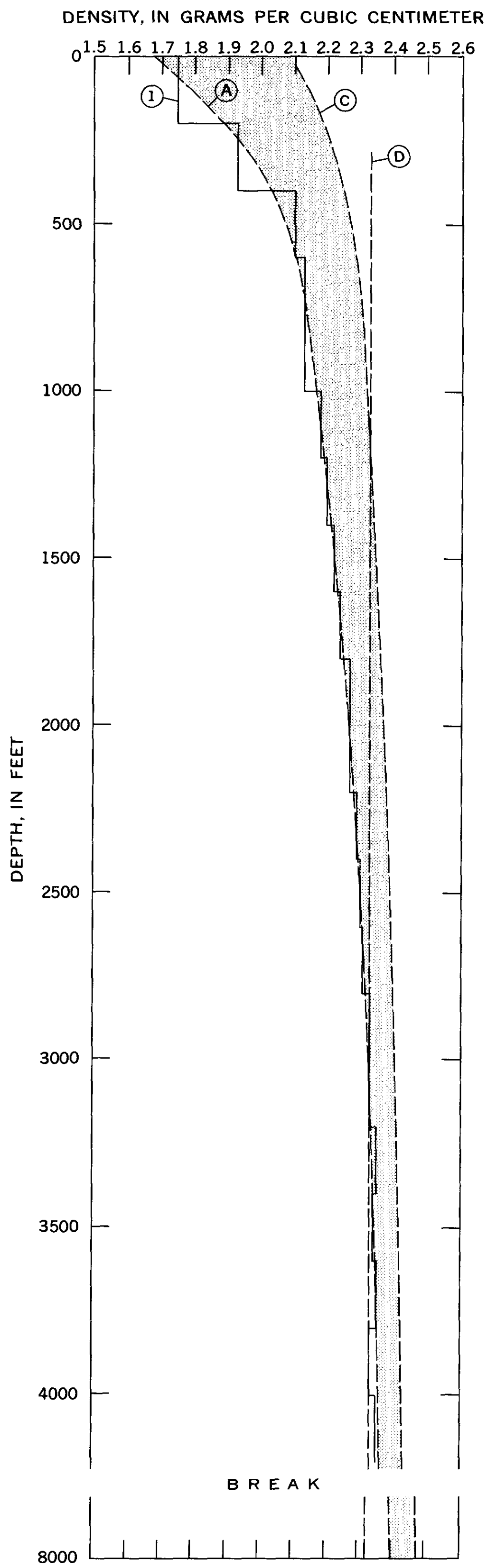
DENSITY DATA

A gamma-gamma density log of the exploration well (well 1) provides the only density control on alluvium for the whole of the western Salt River Valley. A five-point moving average of the upper 1,100 feet of this log is shown in figure 10. With it is a description of lithologies penetrated, based on an examination of drill cuttings. The smooth curve shown with the log was fitted to the log by inspection and represents an idealized density-depth function for the alluvial part of the section. Such a curve is more amenable to use in gravity interpretation than the actual log, which displays pronounced, discontinuous variations. From a depth of 900 feet to the bottom of the well (at 4,503 ft), the gamma-gamma log indicates that the density varies only locally, over very short intervals, from an average value of 2.10 g/cc (grams per cubic centimeter). The cuttings in this interval consist mostly of coarse, clear to slightly cloudy grains and cleavage fragments of halite, plus very minor amounts of silt and clay. A fragment of core from a new well drilled near the exploratory hole and taken from a depth of 3,425 feet was made available to us in April 1971. This core fragment has a crystalline texture and is very coarse grained. Individual halite crystals are moderately clear and have brown inclusions of clay scattered throughout. The value of 2.10 g/cc for the salt interval is higher than the apparent bulk density of 2.03 g/cc noted in other gamma-gamma density measurements of halite (Alger and Crain, 1966).[3]

[3]Although the specific gravity of halite is 2.16, gamma-gamma density logs for pure halite yield a bulk density of only 2.03 because the electron density is not quite proportional to the specific gravity for this mineral.



A



B

FIGURE 11. — Alluvium density logs and idealized depth-density functions used in preparing gravity models of the Luke salt body.

A, Details of uppermost 1,000 feet of logs shown in *B*, plus additional data provided for comparison. 1 and 2, Borehole gravity-meter density logs from alluvium in Hot Creek Valley and Frenchman Flat, Nev., respectively (from Healey, 1970); 3, gamma-gamma density log from Luke area; 4, laboratory core density log from Safford Valley, Ariz.; A, idealized version of 1; B, idealized version of 2; C, idealized version of 3, displaced 0.06 g/cc to the right; and D, constant density used in several of the Luke models.

B, Curve 1 is Healey's (1970) gravity-meter density log from Hot Creek Valley, Nev., from the surface to a depth of 4,200 feet. Smooth curve A, fitted to it and extrapolated to 8,000 feet, was used as a lower bound for our density models and served as a basis for extrapolating curve C (our upper bound) to depths below 790 feet (the top of the evaporite column). Shaded area represents range of variation of density models used in modeling Luke salt body.

We do not know the cause for this discrepancy, but we suspect that it may be the contamination of the salt by included fine-grained clastic silicate minerals.

The data for the alluvial part of the section are shown again but in more exaggerated fashion in figure 11*A* (curve 3). To the right of curve 3 is a smooth curve (C) analogous to the curve fitted to the data in figure 10 but displaced to the right about 0.06 g/cc. This curve represents a maximized density-depth function, and as such it served as a limiting envelope for the various density models we tested. The displacement of 0.06 g/cc was based on a comparison by Healey (1970, fig. 3) of gamma-gamma density log values with borehole gravity-meter values determined in the same well in Hot Creek Valley, Nev. The discrepancy between the two sets of values ranged from 0.01 to 0.09 g/cc for the upper 3,800 feet of the hole and averaged near 0.06. Below this depth the radioactivity log showed much greater variability, and comparisons were more difficult to make. Because we regard the borehole gravity-meter data as the more accurate, the discrepancy of 0.06 g/cc serves as a crude measure of the expectable error of the gamma-gamma data in a borehole in alluvium.

In figure 11*B*, smooth curve C is extrapolated to a depth of 8,000 feet. The extrapolation was guided by additional observations by Healey (1970), who, to our knowledge, is the only investigator who has measured in situ densities in alluvium to great depths. The Nevada base, based on subsurface gravity-meter observations, are the best in existence for estimating the range of densities and illustrating the systematic variations of density with depth in homogeneous alluvial sediments. Smooth curve A was fitted by eye to Healey's data.

The density of the alluvium over the Luke salt body (curve 3 in fig. 11*A*) is appreciably higher than that of the alluvium in Nevada (curves 1 and 2) for equivalent depths. In the depth range 300 to 600 feet, however, it is remarkably similar to values observed in Pliocene (?) sediments in a similar geologic setting (Safford Valley) in southeastern Arizona (curve 4). The contrast with the alluvium in Nevada could be a function of age (Quaternary versus Pliocene) or of differences in grain density or in porosity, which varies widely with pronounced variations in the sorting of alluvium (Eaton and Watkins, 1970). No data on actual grain densities are available for either area (Nevada or central Arizona), but there is good reason to believe that, because of the buoyant rise of the upper part of the Luke salt massif, the porosity of the overlying alluvium has been reduced by compaction, and the density has thereby been increased. If this is the case, the density of alluvium surrounding the flanks of the salt body, at all depths, is probably less than that represented by curve C. Below 1,500 feet, it may also be less than that represented by curve D, an arbitrary averaged constant density employed in a few of our models. We used functions C and D for much of our modeling, although we also tested various densities falling within the shaded area between curves A and C. In so doing we maximized the density contrast between alluvium and salt, particularly in the upper part of the section, and thereby obtained purposefully conservative estimates of the vertical dimension of the salt body.

Note that the crossover depth, above which the density of the salt is greater than that of the surrounding rocks, appears to be unusually shallow in this area. It is about 950 feet for model A and less than 200 feet for model C.

MODELING METHOD

Fourteen three-dimensional gravity models were prepared for comparison with the residual gravity map of figure 9*C*, using density models C, D, A, and others within the shaded area of figure 11*B*. The method of Cordell and Henderson (1968) was used in deriving the models, and the method of Talwani and Ewing (1960) was used in testing them. All three wells that penetrated salt, plus the seven that did not (fig. 8), were used as constraints in preparing the models. Constant density contrasts used in the Cordell-Henderson method were replaced, in the Talwani-Ewing method, by the variable-density models of figure 11. The salt model was modified by hand after each run until a reasonably close fit between the residual gravity field and the modeled gravity field was achieved.

Typical of the final models is the one shown in figure 12. It is based on density model C (fig. 11*B*) and, as such, probably represents a minimum depth (6,900 ft) for the base of the salt. The maximum depth produced by the many models tested was 9,000 feet (using density model A). With the crest of the body at a depth of about 500 feet, the salt body has a vertical dimension somewhere in the range 6,400 to 8,500 feet.

The small solid dots in figure 12*A* represent points at which the gravity field of the model was compared with the residual gravity field. For the 48 stations shown, the average discrepancy between the two values, ignoring the sign of the difference, is 0.3 mgal. The fit is poorest beyond the edges of the body, where the average discrepancy is 0.7 mgal and where the calculated model values are consistently more negative than the residual values. Over the salt itself the average discrepancy, regardless of sign, is only 0.2 mgal. Neither the goodness of fit over the salt nor the poorness of fit beyond the edges of its base constitutes a measure of the accuracy of the model, of course, because the residual anomaly on which the model is based may be in considerable error and because more than one model was derived which gave similar results in terms of matching the residual gravity field. The gross configuration of all these models was roughly the same, however, and all displayed a better fit over the salt than in the area adjacent to it.

The discrepancies observed at points off the structure have several possible explanations. It is well known, for example, that the gravitational effect of a finite slab of given thickness and density varies with depth. As the slab is placed at successively deeper levels in a postulated model, its gravitational effect at a point on the surface over the center of the

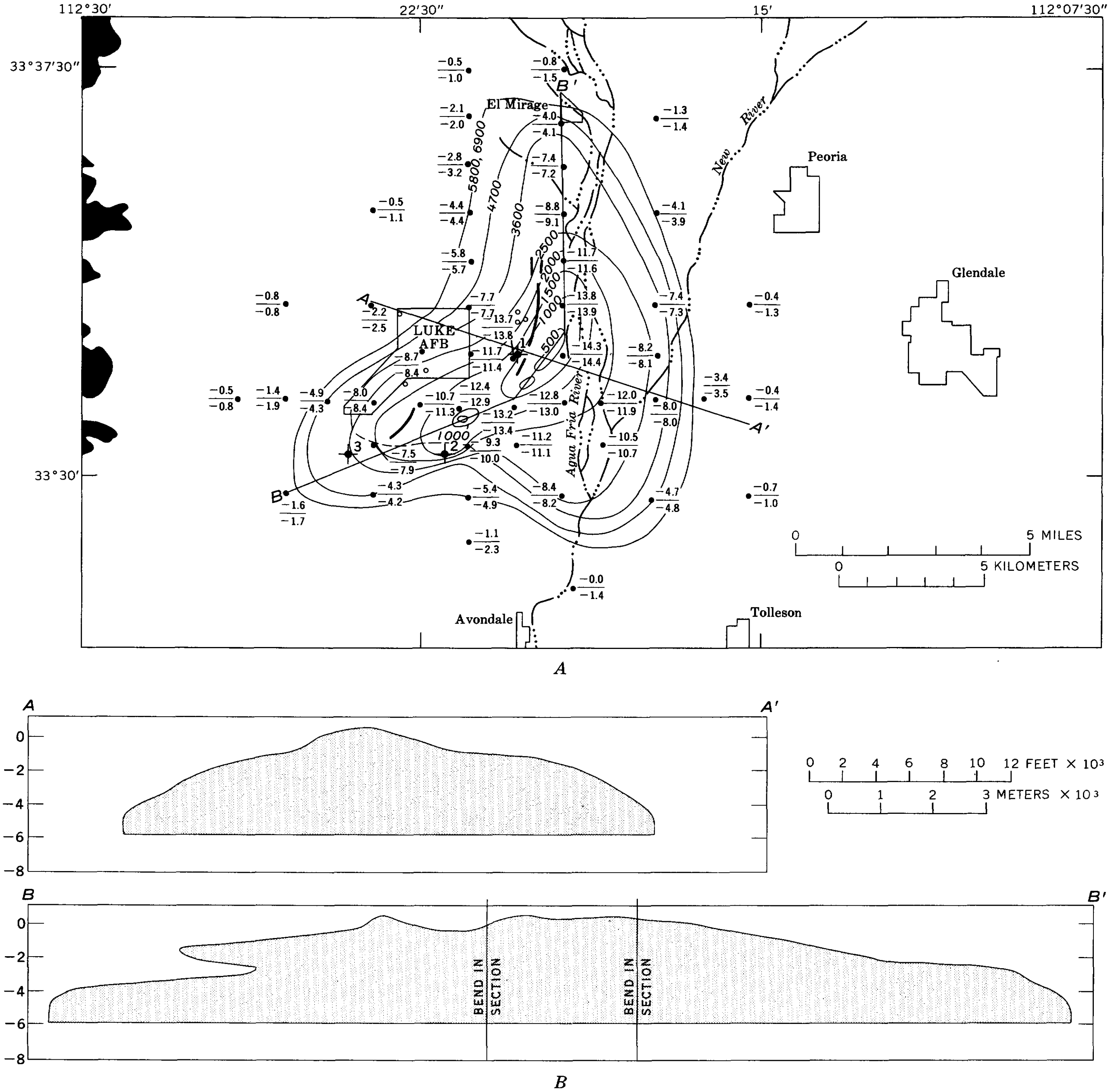


FIGURE 12. — Limiting configurational model of the Luke salt body, based on the residual gravity field of figure 9C and alluvium density model C (fig. 11B). This model has a minimum depth to the base of the salt; all other models tested had deeper bases and, therefore, greater vertical dimensions.

A, Map of the salt body. Depth contour lines are referred to a surface datum. Contour interval is 500 to 1,100 feet. The basal 1,100 feet of the body (5,800 or 6,900) has vertical flanks. Small solid dots are points at which discrete values of the gravity field of this model were calculated. Fraction next to each dot provides a means of comparing values of observed residual gravity from figure 9C (numerator) with those of the modeled gravity field (denominator). Large solid dots with ticks are wells that penetrated halite. Small open circles are wells with collapsed casings. Heavy curved lines represent open earth fractures, as shown in figure 2. Solid pattern represents areas of exposed bedrock.

B, Cross sections *A–A'* and *B–B'* through the salt body. No vertical exaggeration. Numbers on vertical scale are altitudes relative to sea level, in thousands of feet.

slab becomes smaller, but at a point not far off the edge its effect increases slightly with an increase in depth, because the gravitational effect is proportional to the angle subtended by the slab. The practical result is that, as additional slabs are added to the base of a model to bring the calculated values of gravity over the model in line with the observed values, the effects at points just off the edge may be disproportionately large and lead to a poor fit in that area. This was suspected as a prime cause of the poor fit observed off the edges of models such as that in figure 12, but other models prepared to eliminate this effect by placing the base of the salt at shallower depths required what we regarded as unrealistically high values for the density contrast between salt and alluvium, in order to produce correct values at points above the salt. We prefer to think that the residual map itself is in error toward the edges of the anomaly, that the body may interfinger laterally with the enclosing sediments and therefore lack the sharp boundaries suggested by figure 12*B*, or, more likely, that the body tapers inward toward its base. No basis exists for choosing between these hypotheses short of independent geophysical measurements or deep drilling. If the flanks are serrated and taper downward, however, the configuration would be consistent with the facies interpretation described below and illustrated in figure 13*B*.

The gross shape of the model in figure 12 is unlike that of most deformed salt structures known to us. In plan, the basal part is crudely triangular. It is surmounted by a broad ridge trending in an arc southwest to north, the crest of which is marked by several domelike bulges which reach within 500 feet of the surface. At the southwest end of the body there is an overhang in the area of wells 2 and 3.

If one visually eliminates the southeast corner of the model (particularly that part of the body southeast of the 2,000-ft contour), the remainder approximates the core of an arcuate salt anticline. (For comparison, see Byerly and Joesting, 1959, figs. 19, 20, and 21.) Thus one interpretation of the model is that it represents a large plastically deformed mass of salt that has undergone extensive flowage in response to tectonic deformation and (or) to the motive force stemming from the density contrast between the salt and the overlying alluvium. As such, the body would have deformed and shouldered aside a very large volume of valley-fill sediments. Unfortunately, the only subsurface structural data available for testing this hypothesis come from a single well (fig. 8, the 2,003-ft-deep well southwest of Peoria). There the sediments near the bottom of the hole dip at 30°, but in an unknown direction. The question of lateral deformation resulting from doming of the salt is thus unanswerable. Nevertheless, in our preliminary interpretation (Eaton and others, 1970) we referred to the body, in its entirety, as a halokinetic dome, and this is still the preferred interpretation. We were strongly impressed by the doming of the alluvium immediately over the crest of the body, by the localized development of open fissures at the surface, and by the presence of 90 feet of capping anhydrite at well 1. We envisioned, by analogy, an elongate structure somewhat akin to that of a Gulf Coast salt pillow, aided in its initial formation, perhaps, by northwest-trending compression.

We interpreted the cap as a residue of insoluble anhydrite which was originally included throughout the mother salt body as primary evaporite grains and which had accumulated at the crest of the dome in response to solution of the rising halite by undersaturated ground waters. As is well known, marine halite contains 1 to 3 percent insoluble minerals, most of which is anhydrite. The solution of large volumes of such halite leads to the accumulation of several tens to hundreds of feet of anhydrite caprock atop the typical Gulf Coast salt dome. The areal distribution of such caps on some domes is very uniform (Murray, 1961, figs. 5.24 and 5.98), but on other domes, such as the Luke massif, it is very irregular (Murray, 1961, figs. 5.8, 5.16, and 5.99). We believed, therefore, that the facts all pointed toward a large salt dome or pillow, somewhat irregular in plan.

Now, however, in the light of additional data, we believe that the salt body can be justifiably interpreted as an in situ evaporite facies of the valley-fill section. As such, it would represent a stratigraphically extensive, but geographically restricted, prism of evaporites interfingering laterally with the clastic valley fill. The flanks of the body, except where locally faulted, would constitute the loci, through time, of the margins of a restricted lagoon or saline lake which shrank fairly steadily as the halite accumulated, rather than quaquaversally domed, conformable contacts or structural boundaries stemming from diapirism. In the evaporite-prism interpretation, only the uppermost part of the body would have been involved in actual doming, though the dome thus formed would have been nourished by plastic flow from deeper levels in the body. The doming, as well as the open earth fractures and collapsed wells, would be a local phenomenon marking a restricted amount of deformation. The overhang at the southwest end of the body, viewed in the salt-pillow structural interpretation as the product of lateral flow or mushrooming, would represent a temporary south-

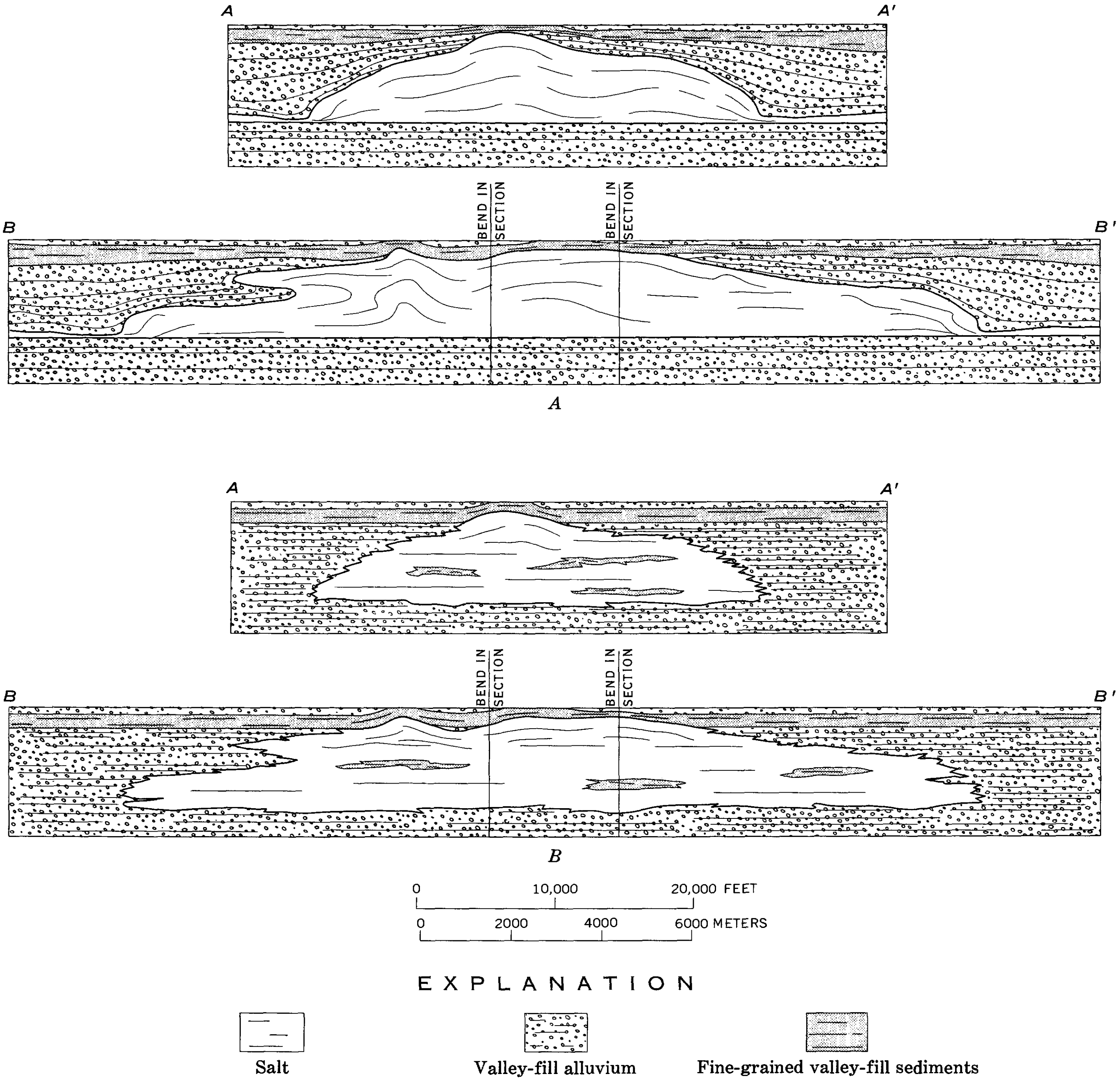


FIGURE 13. — Alternate interpretations of the Luke salt body. *A*, Salt dome or pillow. *B*, In situ evaporite prism, only the top of which has been domed. Interpretation *A* is preferred. Cross-section locations shown in figure 12.

westward transgression of the saline lagoon or playa. Schematic models representing these alternate interpretations and based on cross sections *A–A'* and *B–B'* of figure 12*B* are shown in figure 13.

Evidence that supports the evaporite-prism interpretation follows:

1. Analysis of the insoluble residue in a core from a depth of 3,425 feet in a new well indicates that the total insoluble mineral content of the Luke halite is less than one-half of 1 percent by weight. X-ray diffraction analysis reveals that about 95 percent of these insolubles consists of clay, quartz, feldspar, and calcite. The anhydrite content is, at the most, only 0.025 percent (R. J. Hite, oral commun., 1971). If this single sample is at all representative—and we acknowledge that it may not be—the anhydrite cap atop the Luke body probably is not the result of leaching of a large volume of rising halite. Pos-

sibly the cap represents a primary anhydrite deposit laid down at the close of halite deposition as a result of changes in the composition of the source waters.

2. In well 3, the depth interval from 2,318 to 2,784 feet has been described as "rock salt with interbedded sandstone and conglomerate" (E. E. Komie, written commun., 1964). This description, though admittedly vague, suggests an interfingering of halite with clastic sediments, rather than a laterally intruding tongue of plastically flowing halite.

3. Detailed examination of the neutron porosity log and the compensated gamma-gamma density log for well 1 shows about 20 widely separated intervals, 1 to 4 feet thick, where both the porosity and the density increase sharply within the halite section. These can be interpreted readily as interbedded clastic sediments.

4. In the Dead Sea area of the Middle East, about 4,000 meters (13,000 ft) of salt (El Lisan) is reported to interfinger toward the margins of the rift valley with an equally thick sequence of coarse and fine clastics (Bentor, 1968, p. 143). This occurrence provides a prototype model for the stratigraphically extensive facies variation proposed here for the Luke massif.[4]

ORIGIN OF THE SALT

The origin of the Luke halite is problematic. Neither its age nor its specific mode of accumulation is known, and although we here present some geochemical data bearing on the salinity of the waters in which it was deposited, the interpretation of ultimate origin is closely tied to the problem of age, as explained below. Inferences based on regional geologic observations provide some loose guidelines as to age, but they hardly serve as sharply limiting constraints. What follows, therefore, is offered by way of defining the various geologic constraints that can be arrayed before any proposed hypothesis of origin. It is not yet possible to offer a theory of origin for the Luke salt body that accommodates all the known facts without additional data.

The problem of origin is particularly significant when viewed from the perspective of the volume of the salt, which we estimate to be between 15 and 30 cubic miles. Such volumes are not known among continental evaporite deposits in the Western United States. At least one apparently comparable volume of alleged continental salt elsewhere in the world has been reported (Bentor, 1968, p. 155), but it appears to be exceptional. In most instances, volumes of halite on the order of tens of cubic miles represent marine accumulations. Thus the first step in determining the origin of the Luke salt was to establish whether it was of marine or continental origin. This was done by measuring the bromine content of the halite.

BROMIDE GEOCHEMISTRY

Bromide minerals, as is well known, are not found among the crystallization products of marine waters, even though such products have an appreciable bromine content (Valyashko, 1956; Holser, 1966; Raup, 1966). Instead, the bromine occurs in solid solution, substituting for chlorine in the precipitating chloride minerals. The amount of bromine occurring in the various chlorides is a function of the amount of bromine in the original solution and the coefficients of solid solution of the individual chloride minerals. The abundance of bromine in halite is dependent on the concentration of bromine in the parent solution but is not affected by the presence or absence of other chlorides. As a result, the salinity of the brine from which the halite precipitated can be determined from the bromine content of the halite. Holser (1966, p. 268–270) surveyed the bromine content of a number of basal marine halite deposits of various geologic ages from around the world and found a general tendency for them to fall in the range 30 to 50 ppm.

Theory suggests, and actual sampling confirms, that the bromine content of a salt bed is minimal at the base and that it increases upward, reflecting an increase in salinity of the brine during the period of precipitation. (See, for example, Raup, 1966, figs. 3–6.) Thus the value of 30 ppm obtained by Holser in his survey of basal marine salts represents a threshold value for marine halite. Values of less than 30 ppm bromine represent either nonmarine deposition of the halite or the leaching or dilution of bromine in halite after marine deposition, through the agent of nonmarine or brackish waters. Recrystallization in the dry state will not lower the initial bromine content according to Wardlaw (1970), and this hypothesis is borne out by the values (34 to 89 ppm) measured by Holser (1966, p. 256) in two intensely deformed piercement domes of marine salt in the Gulf Coast region.

No cores from the drilling of the Luke massif were available to us, but extensive samples of cuttings were. Because Raup, Hite, and Groves (1970) have shown that bromine profiles determined from cuttings closely resemble those obtained from cores, we decided to determine the bromine content of the Luke halite from cuttings. From each of 30 samples taken

[4] A difference of opinion concerning the nature of the El Lisan salt body exists in the literature. Picard (1965, fig. 2, sec. 4) depicted it as a "salt horst," and Bender (1968, p. 162 and fig. 151b) described and illustrated arching and faulting of the rocks immediately overlying it, relating these phenomena to ascent of the salt. In cross section B of his geologic map of Jordan, however, Bender (1968) showed the El Lisan salt interfingering laterally with its enclosing rocks over an incomplete stratigraphic interval of 2,000 meters, much in the manner that Bentor (1968) described.

from the depth interval 985 to 4,495 feet in well 1, groups of grains were picked under a binocular microscope. The bromine content of these grains, as determined by X-ray fluorescence, ranged from less than 1 to 6 ppm and averaged 2 ppm. Thus, all values were well below the threshold value indicative of marine halite.

The log of the bromine content in well 1 is shown in figure 14 along with observed values for basal marine halites in the Western Hemisphere and highly deformed marine salt of the Gulf Coast. It seems unlikely that the processes of resolution by fresh or brackish water and subsequent crystallization—phenomena that would be required to produce these low values in marine salt—would have acted on the Luke body to depths of 4,500 feet. We therefore conclude that the Luke halite is probably of nonmarine origin. The analysis of the insoluble minerals in the halite, described earlier, tends to corroborate this interpretation, because the insolubles content was much lower than that of typical marine halites, and the composition was different. The salt probably was deposited in a saline lake.

THE SOURCE PROBLEM

If the Luke salt body is of lacustrine origin, as just suggested, one is led to inquire as to the source of the sodium chloride, which had to be available in great abundance. In raising this question for continental accumulations in general, Stöcklin (1968, p. 417) argued that

> cumulative salt thicknesses of the order of 100 m, (and more) may * * * form in closed continental basins, provided sources other than the open sea, *e.g., salt from older formations,* are available. [Italics ours]

Regarding this problem for the continental Virgin Valley salt deposits in the Muddy Creek Formation of southern Nevada, Mannion (1963, p. 174) postulated older halite deposits on the Colorado Plateaus as the source of the saline waters. It is tempting to cite here an analogous source, the marine evaporites in the Permian upper part of the Supai Formation in the Holbrook basin (Peirce and Gerrard, 1966), as a source for the sodium chloride waters that deposited the Luke halite. The location and extent of this Permian salt is shown in figure 15 as stippled area C. Near it is a large area of saline ground water (diagonally ruled area "a") which occurs in an overlying stratigraphic unit, the Permian Coconino Sandstone. The difficulty in postulating this region as a source for the waters which nourished the Luke deposit is that there is no drainage from the Holbrook basin to the southwest today and little likelihood that there was in the relevant part of the geologic past. The basin lies structurally below the Mogollon High-

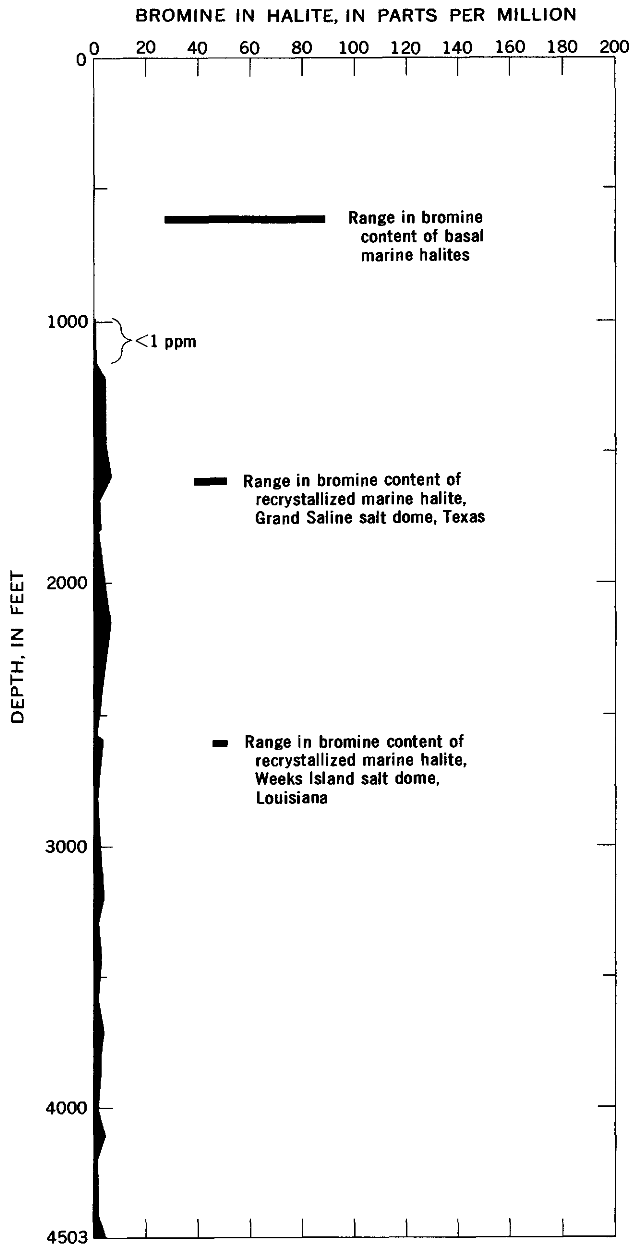


FIGURE 14. — Bromine content of halite in the Luke salt body. On the left, 30 samples of Luke halite, collected from depths of 985 to 4,495 feet, show a range in concentration from less than 1 to 6 ppm. Shown for comparison are the ranges in bromine content of undeformed marine halites of a wide variety of geologic ages from the Western Hemisphere (upper bar) and two severely deformed marine halites from the Gulf Coast of the United States (lower bars). Latter data are from Holser (1966).

lands to its south and southwest and probably did so in mid-Tertiary and later time. The paleogeographic maps of Cooley and Davidson (1963) and Cooley (1967, figs. 7 and 8) show an ancestral Mogollon

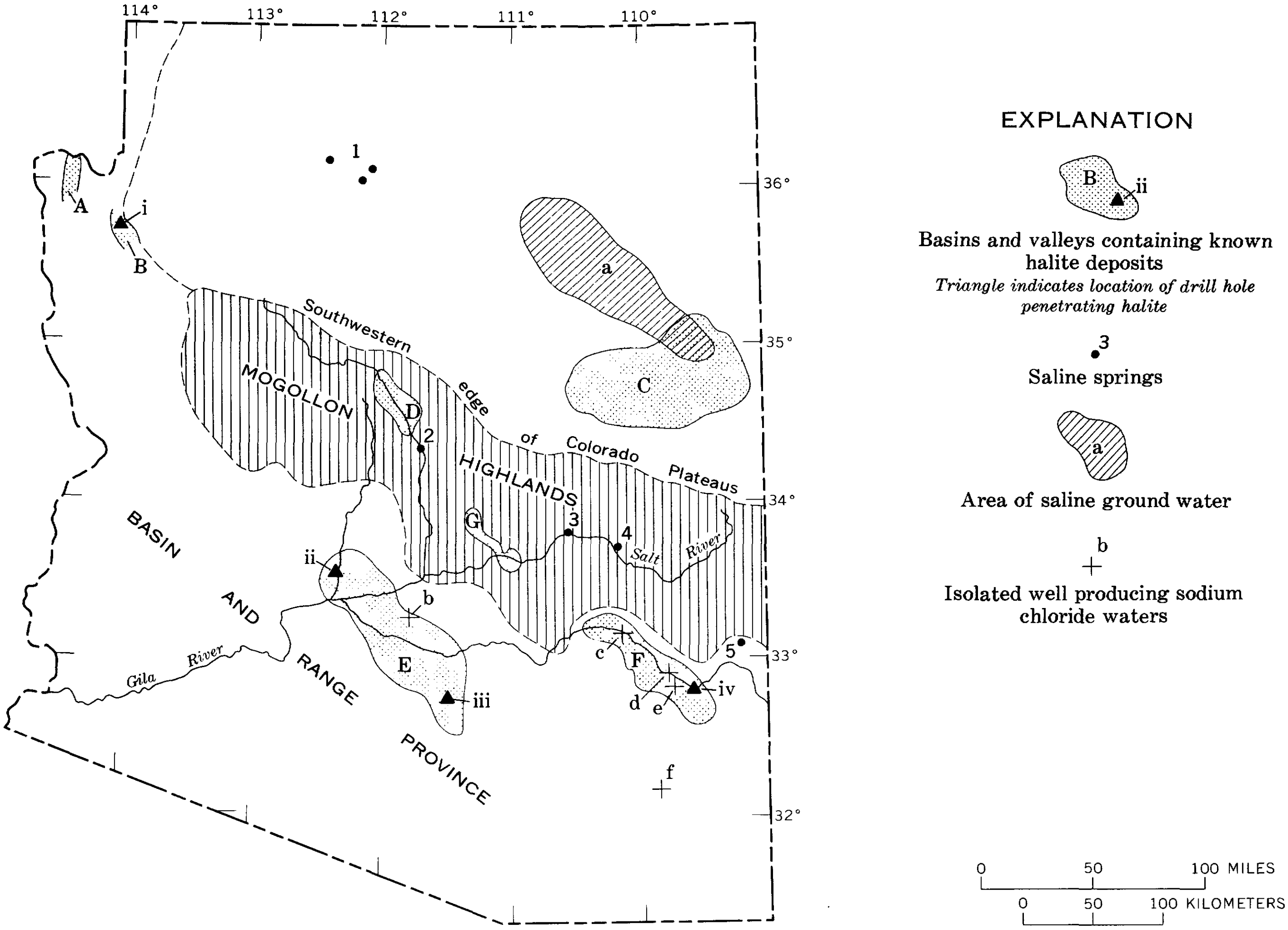


FIGURE 15. — Areas of occurrence of known major halite deposits and sodium chloride waters in Arizona. (See table 1 for full description, including sources of information for drill holes penetrating halite.) Halite, apparently of nonmarine origin and supposed Pliocene age, occurs in substantial quantity in Detrital Valley (A) and Hualpai Valley (B). Marine halite of Permian age occurs in the Holbrook basin (C) on the Colorado Plateaus. Nonmarine evaporites and subsurface brines are found in the Verde Valley (D), although the proportion of sodium chloride is relatively low. Other areas discussed in the text are Phoenix basin (E; outline is that of Cooley and Davidson, 1963, fig. 11), Safford Valley (F), and Tonto Basin (G). Salt springs occur at localities 1 through 5, and ground waters with notable sodium chloride content occur at localities "a" through "f." Area of the Mogollon Highlands is shown by the vertically ruled pattern.

Highlands forming a regional drainage divide between the Colorado Plateaus, where the Holbrook basin is located, and the Basin and Range province, from middle Tertiary (Oligocene) time onward. Still earlier in the Tertiary, before the Colorado Plateaus and Mogollon Highlands were elevated with respect to the Basin and Range province, the regional drainage was apparently northeastward across the relevant part of the region (Cooley, 1967, fig. 6). Thus if the Luke salt body is of Cenozoic age, it apparently could not have been derived, either directly or indirectly, from the Permian marine salt of the Holbrook basin.

Other sources of sodium chloride brines (saline springs 1 through 5 in fig. 15 and table 1) are present in scattered parts of the State, and these, or others like them, may have existed at the time of Luke salt deposition. Springs of this type, as shown in table 1, issue from such widely divergent rocks as Precambrian quartzite, Cambrian sandstone, and Cenozoic volcanics. The ultimate origin of the salt in these spring waters is not known. Two or three of these springs (3 and 4, and possibly 5, in fig. 15) are furnishing sodium chloride to the western Salt River Valley today.

Figure 6 indicates that ground water in the south-

TABLE 1. — *Occurrence of halite and selected sodium chloride brines in Arizona*

Map symbol (fig. 15)	Location of stratigraphic unit	Source of information	Remarks
	Basins and valleys that contain known halite deposits		
A	Detrital Valley	Pierce and Rich (1962, p. 65); Peirce (1969, p. 420).	Relatively pure recrystallized halite. Thickness in subsurface: 500–700 ft. Probably occurs in the Pliocene Muddy Creek Formation (continental origin). Total area of occurrence not known.
B	Hualpai Valley	Pierce and Rich (1962, p. 65); (i) Gillespie, Bentley, and Kam (1966, p. 31-34).	Medium to very coarse grained halite. Some clay inclusions and minor silt, clay, and sand partings. Thickness of halite in subsurface exceeds 1,190 ft by an unknown amount. Thought to occur in the Pliocene Muddy Creek Formation (continental origin). Total area of occurrence not known.
C	Holbrook basin	Peirce and Gerrard (1966)	485 ft (maximum thickness) of halite in the Permian upper part of the Supai Formation (marine origin). Total area of occurrence of halite, 2,300 sq mi.
D	Verde Valley	Twenter and Metzger (1963)	Interbedded evaporites and fine clastic sediments in the Pliocene Verde Formation (continental origin). Evaporites include thenardite, mirabilite, halite, and glauberite. Aggregate thickness not known, but some beds consisting primarily of evaporites are as much as 70–90 ft thick. Total area of occurrence: 75 sq mi.
E	Phoenix basin	(ii) Present report	Luke salt body, confirmed by drilling; relatively pure halite from 880 ft to total depth at 4,503 ft.
		(iii) E. E. Komie, U.S. Bureau of Reclamation (written commun., 1964).	USBR test hole (D–7–8) 25ccc. "Colorless, transparent, crystalline halite" from depth of 1,936.5 ft to total depth at 1,944 ft.
F	Safford Valley	(iv) M. W. Edington (oral commun., 1971).	Test boring (D–7–26) 26aba. "Solid rock salt" from depth of 2,329 to 2,339 ft, underlain by "hard clay" to total depth of 2,350 ft.
	Springs that contain salt water		
1	Several unnamed springs in Garnet Canyon, Phantom Canyon, and Monument Creek, all in Grand Canyon National Park.	Studevant (1926)	Sodium chloride brine issues from springs in the Lower and Middle Cambrian Tapeats Sandstone. No data on salinity or temperature, but halite incrustations are deposited around spring orifices.
2	Verde Hot Springs	Feth and Hem (1963, tables 4 and 5).	Springs issue from Cenozoic volcanic rocks. Total dissolved solids: 3,100 ppm. Chloride: 545 ppm. (Also abundant bicarbonate and sulfate ions.) Discharge: ~10 gpm. Temperature: 100°–106°F.
3	Green Seep at Salt Banks	do	Springs issue from Precambrian quartzite. Total dissolved solids: 28,400 ppm. Chloride: 15,900 ppm. Discharge: no data. Temperature: 70°–78°F.
	Orange Spring at Salt Banks	do	Springs issue from Precambrian quartzite. Total dissolved solids: 37,300 ppm. Chloride: 20,800 ppm. Discharge: no data. Temperature: 70°–78°F.
4	White River Salt Springs	do	Springs issue from Cambrian sandstone and Precambrian quartzite. Total dissolved solids: 8,450 ppm. Chloride: 4,420 ppm. Discharge: ~10 gpm. Temperature: 83°F.
5	Clifton Hot Springs	do	Springs issue from Cenozoic volcanic rocks. Total dissolved solids: 9,790 ppm. Chloride: 5,800 ppm. Discharge: 1,100 gpm. Temperature: 120°F.
	Stratigraphic units in which brines have been reported from water wells		
a	Coconino Sandstone (Permian). Stippled area shows geographic extent of salty ground water.	Cooley, Harshbarger, Akers, and Hardt (1969, fig. 17 and table 8).	Maximum total dissolved solids: 30,000 ppm. Maximum chloride: 10,100 ppm. Lies stratigraphically above halite occurrence in Holbrook basin. (See above.)
b	Valley-fill alluvium (age unknown).	M. E. Cooley, (written commun., 1971).	Water from well (D–1–6) 27dda "has strong salty taste and develops white coating on drying"; depth interval 1,590 to 1,940 ft.
c	Valley-fill alluvium (lower Pleistocene).	M. E. Cooley and E. S. Davidson, (written commun., 1971).	Water from shallow wells. Total dissolved solids: 5,000 ppm. Chloride: 2,500 ppm.
d	Valley-fill alluvium (Quaternary).	Hem (1950, p. 41-56, 148-167).	Water samples from several tens of wells over an area of 10–15 sq mi. Total dissolved solids: ~2,000–7,000 ppm. Chloride: >1,000 ppm. Gila River water shows increase in sodium and chloride in this area.
e	Valley-fill alluvium (probably Pliocene).	Peirce (1969, table 37); E. S. Davidson, (oral commun., 1971).	Water sample from depth of 1,250 ft. Total dissolved solids ("largely sodium and chloride"): 120,000 ppm.
f	Playa sediments (Quaternary).	Brown, Schumann, Kister, and Johnson (1963, p. 82).	Water sample from shallow auger hole. Total dissolved solids: 106,000 ppm. Chloride: 40,500 ppm.

ern part of the western Salt River Valley, near and west of the confluence of the Salt and Gila Rivers, contains a relatively high proportion of dissolved solids. According to McDonald, Wolcott, and Hem (1947), waters of the Salt River have a moderately high dissolved-solids concentration and contain mostly sodium and chloride ions. The Gila River has about the same average concentration as the Salt River but contains proportionately more calcium and sulfate ions and fewer sodium and chloride ions.

The Salt River takes its name from salt springs in its upper reaches (Granger, 1960). Feth and Hem (1963), who sampled the springs at Salt Banks (site 3 in fig. 15 and table 1) commented (p. 37–40):

> Salty water emerges from quartzite of Precambrian age along the Salt River, notably at the junction of the Black and White Rivers and at the Salt Banks. The water from springs at the Salt Banks has a concentration of dissolved solids approximating that of sea water. With the exception of chloride, however, the proportions in which the constituents appear in the spring water are very different from those of sea water. Sodium and chloride greatly exceed other components of the Salt Banks spring inflow, giving the flow practically the character of a solution of common salt * * *. The strata from which these saline springs issue are deeply buried in the area

north of the Salt River Canyon * * * and * * * it seems likely, therefore, that the saline waters * * * may derive much of their dissolved matter from rocks other than the ones from which the springs flow.

Another saline spring (site 4 in fig. 15) occurs approximately 25 miles upstream on the Salt River.

Similarly, the Gila and Verde Rivers, which also enter the western Salt River Valley, both have saline springs in their drainage areas (sites 5 and 2, respectively, in fig. 15), and the Gila flows through a valley (F) containing salty ground water (locs. c, d, and e) and at least one locality of known subsurface salt (iv), indicating earlier deposition of halite. Aggregate discharge and salinity data (McDonald and others, 1947) for these three rivers (Salt, Gila, and Verde) indicate that under present-day conditions a total volume of salt equal to that of the Luke salt body is carried into (and through) the western Salt River Valley in a period of about 20,000 years. If transport by the three rivers was the mode of origin of the Luke halite, however, it would have been necessary for the basin to have been closed to through-flow of the Salt River and its tributaries, and an additional, but unknown, period of time would have been required for evaporation. In addition, the load of clastic sediments that these rivers would have carried in traction and suspension would have to be reconciled with the total volume of clastic sedimentary rocks filling the balance of the western Salt River Valley in order to adequately test the hypothesis.

Attractive as this hypothesis may seem in attempting to explain the origin of the Luke salt deposit, it conflicts with serious obstacles in the form of the following regional geologic facts given by Cooley (1968, p. 75–77): The main physiographic features and the ancestral stages of the present drainage patterns in southeastern Arizona were developed mainly in Pliocene and Quaternary time. In early to middle Pliocene time, drainage was impounded and basins were internally drained. The Salt and Verde Rivers did not enter the Phoenix basin until late Pliocene to early Quaternary time, and the Gila River, until early post-Blancan time.

These facts are depicted in the paleogeographic maps by Cooley (1967, figs. 7, 8), which show regional drainage divides that would have prevented inflows to the Phoenix basin of surface waters from springs 2 through 5 (fig. 15) from Oligocene time until late Pliocene or later time. Thus if the saline springs described in table 1 were the sources of the Luke salt deposit, the salt would have to be of late Pliocene age or younger. We believe it to be older than this, in spite of the fact that the apparently analogous halite in Virgin, Detrital, and Hualpai Valleys is, or is reputed to be, of Pliocene age.

The Pliocene and Pleistocene deposits of the local region, as noted earlier, are generally less than 2,000 feet thick in the deeper parts of the basins, and some are only 1,000 to 1,200 feet thick. In contrast, the base of the Luke salt body is believed to be at a depth greater than 4,500 feet, and the gravity data suggest it may be as deep as 6,900 to 9,000 feet. Thus the base of the salt would appear to be stratigraphically well below the base of the Pliocene section. If the salt is middle Tertiary in age (Oligocene or Miocene), or still older (for example, Mesozoic) — and no data at present preclude this possibility — the source or sources for the sodium chloride remain a mystery. One can only postulate a source in the Paleozoic or Mesozoic rocks of the ancestral Mogollon Highlands, an admittedly ad hoc hypothesis. Brine occurrences such as that at locality f (fig. 15, table 1) indicate that highly saline waters can accumulate locally in internally drained basins far from any source of abundant sodium chloride, but it is extremely doubtful that one could account for the vast volume of the Luke salt deposit in this way.

If the Luke halite is, after all, contemporaneous with the halite in Virgin, Detrital, and Hualpai Valleys, either the western Salt River Valley is regionally anomalous in having an enormously thick (6,900 to 9,000 ft) Pliocene-Pleistocene section or the halite in those three valleys is not of Pliocene age, as previously thought. Interestingly, some of the observational data for the Virgin Valley deposit seem open to an interpretation of greater age for the salt. In his description of the Muddy Creek section, Longwell (1936, p. 1423) noted that the "salt deposits are low in the section, and are brought to view only where they have been thickened and have domed the overlying beds * * *"; again (p. 1469) "* * * As the salt is seen only where it has been forced up and presumably thickened, its normal horizon within the Muddy Creek formation is not known."

Mannion (1963), who studied these deposits in greater detail later, noted that the salt exposures along the Virgin River are associated with severe structural deformation in the Muddy Creek Formation. He also commented (p. 173) that "near Echo Bay * * * a rather impure, thin salt section rests directly on anhydrite, sandstone, and volcanic rocks which may not belong to the Muddy Creek formation." Thus the halite associated with the Muddy Creek Formation may have originated in older rocks and achieved its present position within the formation by diapirism and doming. If so, then it, too, could be of middle Tertiary or older age.

The occurrence of Cenozoic (or older) halite in Virgin, Detrital, Hualpai, Verde, and western Salt River Valleys suggests that other basins bordering the Colorado Plateaus in Arizona may enclose similar large bodies of salt. Safford Valley, with its several known occurrences of highly salty ground water and one confirmed bed of halite (fig. 15, table 1), and Tonto Basin, in which the Salt River was impounded for a time, both appear to be likely possibilities.

REFERENCES

Alger, R. P., and Crain, E. R., 1966, Defining evaporite deposits with electric well logs, *in* Rau, J. L., ed., Second symposium on salt: Cleveland, Northern Ohio Geol. Soc., v. 2, p. 116–130.

Anderson, T. W., 1968, Electrical analog analysis of ground-water depletion in central Arizona: U.S. Geol. Survey Water-Supply Paper 1860, 21 p.

Bender, Friedrich, 1968, Geologie von Jordanien: Gebrüder Borntraeger, Berlin, 230 p.

Bentor, Y. K., 1968, Salt deposits of the Dead Sea region, *in* Mattox, R. B., and others, eds., Saline deposits — A symposium: Geol. Soc. America Spec. Paper 88, p. 139–156.

Bott, M. H. P., and Smith, R. A., 1958, The estimation of the limiting depth of gravitating bodies: Geophys. Prospecting, v. 6, p. 1–10.

Brown, S. G., Schumann, H. W., Kister, L. R., and Johnson, P. W., 1963, Basic ground-water data of the Willcox basin, Graham and Cochise Counties, Arizona: Arizona Land Dept. Water-Resources Rept. 14, 93 p.

Byerly, P. E., and Joesting, H. R., 1959, Regional geophysical investigations of the Lisbon Valley area, Utah and Colorado: U.S. Geol. Survey Prof. Paper 316–C, p. 39–50.

Cooley, M. E., 1968, Some notes on the Late Cenozoic drainage patterns in southeastern Arizona and southwestern New Mexico, *in* Titley, S. R., ed., Southern Arizona Guidebook 3, Geol. Soc. America Cordilleran Sec., 64th Ann. Mtg.. Tucson 1968: Tucson, Arizona Geol. Soc., p. 75–78.

Cooley, M. E., compiler, 1967, Arizona highway geologic map: Tucson, Ariz., Arizona Geol. Soc.

Cooley, M. E., and Davidson, E. S., 1963, The Mogollon Highlands — Their influence on Mesozoic and Cenozoic erosion and sedimentation: Arizona Geol. Soc. Digest, v. 6, p. 7–35.

Cooley, M. E., Harshbarger, J. W., Akers, J. P. and Hardt, W. F., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geol. Survey Prof. Paper 521–A, 61 p.

Cordell, L., and Henderson, R. G., 1968, Iterative three-dimensional solution of gravity anomaly data using a digital computer: Geophysics, v. 33, p. 596–601.

Eaton, G. P., and Watkins, J. S., 1970, The use of seismic refraction and gravity methods in hydrogeological investigations, *in* Morley, L. W., ed., Mining and groundwater geophysics, 1967: Geol. Survey Canada Econ. Geol. Rept. 26, p. 544–568.

Eaton, G. P., Peterson, D. L., and Schumann, H. H., 1970, Luke Dome — A halokinetic salt mass near Phoenix, Arizona [abs.]: Geol. Soc. America Abs. with Programs, v. 2, no. 5, p. 332.

———1971, Geophysical, geochemical, and geohydrological reconnaissance of the Luke salt structure, central Arizona [abs.]: Am. Assoc. Adv. Sci. 47th Ann. Mtg. and Arizona Acad. Sci. 15th Ann. Mtg., Tempe, Ariz. 1971: p. 46.

Feth, J. H., and Hem, J. D., 1963, Reconnaissance of headwater springs in the Gila River drainage basin, Arizona: U.S. Geol. Survey Water-Supply Paper 1619–H, 54 p.

Gillespie, J. B., Bentley, C. B., and Kam, William, 1966, Basic hydrologic data of the Hualapai, Sacramento, and Big Sandy Valleys, Mohave County, Arizona: Arizona Land Dept. Water-Resources Rept. 26, 39 p.

Granger, B. H., 1960, Will C. Barnes' Arizona place names: Tucson, Arizona Univ. Press, 519 p.

Healey, D. L., 1970, Calculated in situ densities from subsurface gravity observations and density logs, Nevada Test Site and Hot Creek Valley, Nye County, Nevada, *in* Geological Survey research 1970: U.S. Geol. Survey Prof. Paper 700–B, p. 52–62.

Hem, J. D., 1950, Quality of water of the Gila River basin above Coolidge Dam, Arizona: U.S. Geol. Survey Water-Supply Paper 1104, 230 p.

———1959, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 269 p.

Holser, W. T., 1966, Bromide geochemistry of salt rocks, *in* Rau, J. L., ed., Second symposium on salt: Cleveland, Northern Ohio Geol. Soc., v. 1, 248–275.

Kam, William, Schumann, H. H., Kister, L. R., and Arteaga, F. E., 1966, Basic ground-water data for western Salt River Valley, Maricopa County, Arizona: Arizona Land Dept. Water-Resources Rept. 27, 72 p.

Longwell, C. R., 1936, Geology of the Boulder Reservoir floor, Arizona-Nevada: Geol. Soc. America Bull., v. 47, no. 9, p. 1393–1476.

Mannion, L. E., 1963, Virgin Valley salt deposits, Clark County, Nevada, *in* Symposium on salt: Cleveland, Northern Ohio Geol. Soc., p. 166–175.

McDonald, H. R., Wolcott, H. N., and Hem, J. D., 1947, Geology and ground-water resources of the Salt River Valley area, Maricopa and Pinal Counties, Arizona: U.S. Geol. Survey open-file report, 45 p.

Murray, G. E., 1961, Geology of the Atlantic and Gulf coastal province of North America: New York, Harper and Brothers, 692 p.

Peirce, H. W., 1969, Salines, *in* Mineral and water resources of Arizona: Report for the Committee on Interior and Insular Affairs, United States Senate, U.S. Govt. Printing Office, p. 417–424.

Peirce, H. W., and Gerrard, T. A., 1966, Evaporite deposits of the Permian Holbrook basin, Arizona, *in* Rau, J. L., ed., Second symposium on salt: Cleveland, Northern Ohio Geol. Soc., v. 1, p. 1–10.

Peterson, D. L., 1965, Bouguer anomaly map and principal facts for gravity stations for the Central Arizona Project: U.S. Geol. Survey open-file report, 2 p., 5 maps, 57 data sheets.

———1968, Bouguer gravity map of parts of Maricopa, Pima, Pinal, and Yuma Counties, Arizona: U.S. Geol. Survey Geophys. Inv. Map GP–615.

Picard, Leo, 1965, Thoughts on the graben system in the Levant, *in* Irvine, T. N., ed., The world rift system: Geol. Survey Canada Paper 66–14, 22–32.

Pierce, W. G., and Rich, E. I., 1962, Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials: U.S. Geol. Survey Bull. 1148, 91 p.

Raup, O. B., 1966, Bromine distribution in some halite rocks of the Paradox Member, Hermosa Formation, in Utah, *in* Rau, J. L., ed., Second symposium on salt: Cleveland, Northern Ohio Geol. Soc., v. 1, p. 236–247.

Raup, O. B., Hite, R. J., and Groves, H. L., Jr., 1970, Bromine distribution and paleosalinities from well cuttings, Paradox basin, Utah and Colorado, *in* Rau, J. L., and Dellwig, L. F., eds., Third symposium on salt: Cleveland, Northern Ohio Geol. Soc., v. 1, p. 40–47.

Skeels, D. C., 1967, What is residual gravity?: Geophysics, v. 32, p. 872–876.

Stöcklin, Jovan, 1968, Salt deposition in closed continental basins, *in* Mattox, R. B., and others, eds., Saline deposits — A symposium: Geol. Soc. America Spec. Paper 88, p. 417.

Studevant, G. E., 1926, Salt in the Tapeats Sandstone: Grand Canyon Nature Notes, v. 1, no. 6, p. 3–5, Grand Canyon, U.S. Natl. Park Service.

Stulik, R. S., and Twenter, F. R., 1964, Geology and ground water of the Luke area, Maricopa County, Arizona: U.S. Geol. Survey Water-Supply Paper 1779–P, 30 p.

Talwani, Manik, and Ewing, W. M., 1960, Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape: Geophysics, v. 25, no. 1, p. 203–225.

Thornbury, W. D., 1969, Principles of geomorphology, 2d ed.: New York, John Wiley and Sons, 594 p.

Twenter, F. R., and Metzger, D. G., 1963, Geology and ground water in Verde Valley—The Mogollon Rim region, Arizona: U.S. Geol. Survey Bull. 1177, 132 p.

Valyashko, M. G., 1956, Geochemistry of bromine in the processes of salt deposition and the use of the bromine content as a genetic and prospecting criterion: Geochemistry (English translation), p. 570–589.

Wardlaw, N. C., 1970, Effects of fusion, rates of crystallization and leaching on bromide and rubidium solid solutions in halite, sylvite and carnallite, *in* Rau, J. L., and Dellwig, L. F., eds., Third symposium on salt: Cleveland, Northern Ohio Geol. Soc., v. 1, p. 223–231.

Wilson, E. D., Moore, R. T., and Cooper, J. R., 1969, Geologic map of Arizona: Arizona Bur. Mines and U.S. Geol. Survey.

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