GROUND WATER IN FRACTURED VOLCANIC ROCKS IN SOUTHERN ARIZONA

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ABSTRACT

Fractured volcanic rocks, mostly andesitic flows of middle to late Tertiary age, provide only small to moderate amounts of water in southern Arizona. Their water-bearing potential is virtually untested, largely because adequate volumes of water are obtained from shallower and more easily drilled alluvial deposits. Nonetheless, andesitic flows underlie alluvium in many places and are untapped sources of ground water of usable quality.

Wells in andesitic flows locally yield as much as 60 liters per second (1,000 gallons per minute), but yields are highly variable and cannot now be predicted, even within short distances. Yields from volcanic rocks undoubtedly come from interflow breccias and primary voids, as well as fractures, but the proportion of water yielded by each type of opening is unknown, and the combined yields are considered here to represent the water-bearing potential of fractured volcanic rocks.

Fractured volcanic rocks in the basin-and-range country of southern Arizona also underlie areas of recharge in the mountains and act as conduits to transmit water to ground-water reservoirs in the alluvium of the basin fill or in the permeable volcanic rocks buried by or interbedded with the alluvium.

To encourage development of ground water in fractured volcanic rocks, criteria are needed to identify, map, and project the fractures to below the surface. Determination of the relationship of permeability to mode and environment of extrusion and deposition, and to subsequent deformation and erosion, offer the principal means for meeting these needs.

RESUMÉ

Les eaux souterraines dans les roches volcaniques fissurées de l'Arizona méridional

Dans l'Arizona méridional, les roches volcaniques fissurées — constituées pour la plupart d'andesites datant du milieu ou de la fin de l'ère tertiaire — ne fournissent que de faibles ou modestes quantités d'eau, surtout parce que l'eau est obtenue en abondance des roches volcaniques et des couches d'alluvions moins profondes et plus faciles à forer. Cependant, sur de vastes étendues, les coulées andésitiques sont recouvertes de dépôts d'alluvions et représentent à tout le moins des sources locales inexploitées d'eau souterraine dans les bassins d'entremont.

Les andésites de la région fournissent jusqu'à 60 litres d'eau par seconde (1,000 gallons par minute), mais les débits sont très variables et défient toute prédiction, même sur de courtes distances. On ignore quelle proportion de ce débit est due à l'existence de brèches entre les conduits.

Les roches volcaniques fissurées influent sur le mouvement des eaux souterraines dans les couches d'alluvions des bassins d'entremont du fait qu'elles se trouvent au-dessous des zones de recharge, qu'elles servent de conduits, à la surface ou au-dessous, amenant les eaux dans les réservoirs alluviaux souterrains, et qu'elles constituent lorsque leur perméabilité est faible, des barrières souterraines et des barrages de dérivation.

Pour encourager l'exploitation des eaux souterraines dans les roches volcaniques fissurées, il faut établir des critères permettant de déterminer la perméabilité et sa répartition au-dessous des autres dépôts. L'étude du mode d'extrusion et de dépôt, du milieu dans lequel ceux-ci se sont opérés et de la déformation ultérieure est le principal moyen pour établir ces critères.

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INTRODUCTION

Volcanic rocks of many types are exposed extensively in the western part of the United States and yield small to large volumes of water to wells locally. These rocks have not been exploited extensively for water, except where no other source is available, because they are not considered to be reliable aquifers and because adequate volumes of water are obtained from shallower and more accessible and easily drilled alluvial deposits. Their reputation for unreliability results largely from our present inability to predict the distribution of fractures, and thus of well yields, of even closely spaced wells. Nonetheless, volcanic rocks, and particularly fractured flows, represent at least local potential sources of ground water. This report summarizes the general conditions under which water occurs in fractured volcanic rocks in southern Arizona and suggests guidelines for further investigation of the potential productivity of these rocks.

Southern Arizona is in the Basin and Range physiographic province and consists of roughly sub-parallel chains of mountain ranges and intermontane basins (fig. 1). In general, the basins in southern Arizona are more extensive than mountain ranges, in places two or three times as extensive (fig. 2). The mountains are composed mostly of Precambrian and Mesozoic granitic and metamorphic rocks, Precambrian and Paleozoic sedimentary rocks, and Mesozoic and Tertiary volcanic and indurated alluvial rocks. The basins are filled largely with Tertiary and Quaternary alluvial
material, which locally is interbedded with volcanic deposits that are generally younger than those exposed in the mountains. The fill in the central parts of the basins may be nearly 1,000 meters thick. In some basins, isolated hills of bedrock stand above the alluviated valley floors, and in a few basins, all or large parts of the valley floor are composed of volcanic rocks which overlie or are interbedded with alluvial deposits.

Fig. 2 — Relief map of part of southern Arizona showing general distribution of ranges and basins. (Outlined area is Papago Indian Reservation.)

The potential importance of water in volcanic rocks stems from the dependence of southern Arizona on ground water. About two-thirds of Arizona's water needs is now supplied by ground water. The rates of decline of water levels, and of groundwater in storage, of the past few years, based on the analysis of declines in the most heavily pumped areas, are predicted to continue for at least the next few years (White and others, 1964). Almost all ground water is supplied by the most widely distributed rock, the alluvium in the intermontane basins, and locally, the overdevelopment of these aquifers is severe. The second most widely distributed rock of potentially moderate to large water-yielding capabilities is fractured volcanic flows of middle to late Tertiary and Quaternary age. The other principal types of rocks in southern Arizona are nearly impermeable or only of local significance as aquifers.

DESCRIPTION AND GEOLOGIC SETTING

Although nearly all types of volcanic rocks—flows, tuff, agglomerate, and breccia—yield some water somewhere, the discussion here is limited to water in fractured and brecciated andesitic flows, because in southern Arizona they are the second most extensive aquifers. The flows generally are andesitic, but some are latitic or basaltic. Individual flows range in thickness from about 1 to 20 meters, but usually are 5 to
10 meters thick; they may be in sequences from a few to about 500 meters thick. Typically the flow rocks are brecciated and fractured, particularly along their upper and lower surfaces, but hexagonal fracturing resulting from cooling is rarely prominent. At the present time the effects of voids and cavities, brecciation, and fracturing cannot be separated in evaluating the water-bearing potential of large masses of these flows, mainly because most of the data regarding their water-bearing characteristics are reported in summary terms by drillers and well owners. However, available data are adequate to indicate that the flow rocks have permeabilities that range from low to very high and that the permeability may change markedly within short distances, both vertically and horizontally. In some places, well fractured flows are dry because the fractures and cavities are not interconnected.

Andesitic flows cap or form a large part of many ranges in southern Arizona. Their appearance is so uniform over so many tens of thousands of square miles, that it is easy to think of them as remnants of a widespread volcanic plateau, similar to, but smaller than, that of the Columbia and Dekkan fields. However, in southern Arizona the flows came from many separate centers and at different times, and probably never were continuous over the region. Rather, they originated as small shield or composite volcanoes, whose margins may or may not overlap, and in thick sequences built up within the confines of broad, deep valleys. (For examples, see Anderson and Creasey, 1958; Gilluly, 1946; Heindl, 1963; Twenter, 1963.) As a result, the thicknesses of volcanic sequences may differ considerably, and adjacent areas of flows may be different depositional units.

The original form of the volcanic deposits has been modified in turn by structural deformation and erosion. They have been folded, mostly into broad shallow folds, and ruptured, mostly along normal faults. Those volcanic deposits elevated to form topographic highs have been eroded deeply, and those depressed into the basins have been buried. The volcanic rocks that are contemporaneous and interbedded with, or younger than, the basin fill are much less affected by deformation and erosion.

Where the fractured volcanic rocks are buried by or interbedded with the saturated basin alluvium, they may be in hydraulic continuity with the alluvium. Depending on relative permeability, water may move either from or into the volcanic rocks, or, as has been shown in one area (Heindl and McCullough, 1961), the water may move back and forth between volcanic and alluvial rocks, depending on down-gradient changes in permeability.

This brief description presents the main elements by which the ground-water characteristics of the volcanic rocks are categorized in the following section as to their potential value as aquifers and as to the desirability for their exploration and further investigation.

**GROUND-WATER CHARACTERISTICS BY TOPOGRAPHIC SITUATIONS**

The ground-water characteristics of fractured andesitic flow rocks in southern Arizona are here categorized on the basis of their topographic situations, and examples are described briefly. The ground-water characteristics are given on the assumption that the sequences of flows have fairly uniform "formational" permeabilities, although these may differ considerably from the "rock" permeability at any particular site.

The chemical quality of water in volcanic rocks is not discussed because available records indicate the chemical quality is generally uniform. Water from volcanic rocks commonly contains about 300 to 600 parts per million of dissolved solids, and the principal objectionable constituents are fluoride (commonly greater than 1 part per million) and silica (commonly greater than 20 parts per million).
A. *Volcanic flows in mountain ranges*

1. In eroded remnants high in the ranges; no continuity with basin alluvium; (see A-1, fig. 3).

   a) Largely areas of recharge and nearly immediate discharge; small wet-weather springs or seeps at or near base of volcanic sequence, at interfaces between successive flows, or at some fracture intersections; potentially poor aquifer.

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**Fig. 3** — Diagrammatic sketches showing relationship of topographic situation of fractured rocks to the occurrence of ground water.
b) Examples are numerous. Table Top Mountain, Pinal County, stands about 600 meters above the surrounding valleys. The mountain is composed largely of granite and schist, and is capped by volcanic flows which are about 150 meters thick and cover an area nearly 5 square kilometers. Small seeps are marked by patches of vegetation that remain green after the rest of the mountainside has turned brown or gray. Another example is Black Mountain near Tucson, Pima County, which stands about 300 meters above the surrounding piedmont slope. Black Mountain is a fault block about 3 kilometers long and 0.5 kilometer wide. It consists mainly of about 150 meters of volcanic flows resting on consolidated, poorly permeable conglomerate which is older than the alluvium of the basin fill. Wet-weather springs are localized along the base of the volcanic flows by small transverse faults. The volcanic flows and associated dikes are aquifers where they are encountered below the alluvium and the water table in adjacent areas. Locally these volcanic rocks yield small quantities (1 to 10 liters per minute) to domestic and stock wells (Heindl and White, 1965).

2. In eroded remnants that pass beneath the basin alluvium. (See A-3, fig. 4).
   a) Form areas of recharge in mountains and transmit water to below water table; depending on structural relationship and extent, they may or may not be a usable aquifer.
   b) Many examples, including Vaca Hills and Mesquite Mountains, Pima County, and west side of Vekol Mountains, Pinal County. The northern of the two Vaca Hills is capped by about 50 meters of vesicular and fractured volcanic flows which dip north and pass under the valley fill. A well 6 kilometers west of the Mesquite Mountains obtains water from lava at a depth of about 160 meters below the surface and about 30 meters below the base of the alluvium.

3. Constitute a large proportion of the range and pass under the alluvium. (See B, fig. 5).
   a) Form large areas of recharge and transmit water to saturated zone; potentially a usable aquifer.
   b) Many examples, including Ajo Range and Sikort Chuapo and Batamote Mountains, Pima County, and the mountains flanking Eagle Creek, Greenlee County. At least 6 test holes were drilled generally within about 300 meters of each other in the alluvial fill along Eagle Creek. Andesitic flows were penetrated at depths of 60 to 100 meters. Hot water (ranging from about 48 °C to 56 °C) under artesian pressure rose to within a few meters of the surface or flowed at low rates. When tested with pumps, the wells yield from about 10 to 60 liters per second. However, a long-term (6 months) pumping test by C. F. Tolman in 1939 is reported to indicate that the aquifer had a “safe yield” of only about 60 liters per second. Detailed records of the test are not accessible to determine what was meant here by the term “safe yield.” In Bonita Creek, Graham County, about 30 kilometers east of Eagle Creek, the volcanic rocks in the basin have supplied the city of Safford with about 100 liters per second for many years (Heindl and McCullough, 1961). This water, however, is not obtained directly from volcanic flows; instead, it is obtained from shallow and narrow channel deposits which partly fill a canyon cut into the volcanic rocks. The water moves into the channel fill because a local barrier in the volcanic rocks, possibly an impermeable fault zone, prevents the water from continuing downgradient in the volcanic rocks.

B. Volcanic flows in basins

1. Widespread flows and related features (cinder cones) at surface; (see A-2, fig. 6).
   a) Form large areas of recharge; transmit water readily to water table; may or may not be an aquifer depending on whether the sequence is thick enough to be below saturated zone.

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b) San Bernardino Valley, Cochise County, includes about 450 square kilometers of volcanic flows and cinder cones at the surface. Alternating beds of volcanic and alluvial deposits locally are at least 300 meters thick. The water is under sufficient artesian pressure locally to flow at rates of as much as 6 liters per second, but generally the water levels are from less than 50 to nearly 300 meters below land surface. A second, and somewhat different example, is that of the Sentinel flows in Maricopa County. These flows occupy about 650 square kilometers, but they apparently lie above the water table and do not yield water to any known wells.

2. Restricted exposures in small hills standing above basin fill.

a) Isolated hills are exposed parts of sequences of volcanic deposits intercalated with surrounding alluvium. (See C, fig. 3). Buried volcanic deposits probably are recharged largely from basin fill and may form potentially useful aquifers. In the broad valley known as the Dateland-Hyder area, along the boundary between Maricopa and Yuma Counties, sequences of volcanic flows intercalated with alluvial deposits range in thickness from about 100 to 400 meters and are at different depths below the surface to a maximum of 700 meters. Exposures of volcanic rocks in adjoining mountains are widespread and of different ages, but only 4 or 5 small hills in a valley area of about 1,200 square kilometers hint at the presence of buried volcanic rocks. Yields from wells range from about 60 to 150 liters per second. The amounts contributed separately by the volcanic rocks and the intercalated alluvial deposits are not known. However, the fact that yields from wells that penetrate volcanic flows commonly are slightly greater to roughly twice as great as those from the alluvium alone suggests that the buried volcanic flows are aquifers. (Summary based on well data compiled by W. G. Weist, Jr., U.S. Geological Survey, Tucson, Arizona.)

b) Isolated hills are exposed parts of small fault blocks or slivers. (See D, fig. 3). Such blocks of volcanic rock may or may not be in hydraulic continuity with alluvium, depending to some extent on permeability of fault gauge and degree of fracturing along the fault plane; may be a questionable or highly localized aquifer. In the central part of the lower San Pedro River basin in Pinal County, three small volcanic hills, all less than one square kilometer in extent, are in fault, or probable fault, contact with the alluvial deposits of the basin. The volcanic rocks are fractured and interflow contacts are brecciated and apparently porous. These rocks could be sufficiently permeable to transmit water, but no wells have been drilled into them.

c) Isolated hills are exposed parts of volcanic sequences which may or may not be exposed in adjacent ranges. The buried volcanic rocks are in hydraulic continuity with the alluvium beneath which they are buried. The adequacy of volcanic rocks as aquifers in this situation depends largely on their extent. Several examples of this situation are known, such as in the upper Hickiwan and upper La Quitani Valleys of Pima County; the outstanding example is Childs Valley, generally north and east of Ajo. Ajo is a copper mining center, and its operations require large volumes of water for mine, mill, smelter, and municipal purposes. For 40 years nearly all of the supply has been from wells about 6 kilometers north of Ajo. Early in the century, a shaft was sunk to a depth of about 230 meters into andesitic flows and breccias, which lie beneath about 60 meters of alluvium. Drifts branched out from the bottom of the shaft, which was at the water level of that time, to collect water moving through the brecciated volcanic rock. When the water level threatened to drop below the bottom of the drifts, a well was drilled in the bottom of the shaft to a depth of about 410 meters. Subsequently, 300-meter deep wells were drilled from the surface to tap the same volcanic aquifer, but the principal production continued from the "shaft well," at least to 1956, the last year for which a report is available. Between 1913 and 1956, the water level had dropped 13 meters. In 1956, the well field produced 24 cubic meters per minute. In the past
decade, operations at the mine and the population of Ajo have expanded, and the pumpage now probably is in the order of about 30 cubic meters per minute.

C. No exposures of volcanic rocks in basin. (See E, fig. 3).

a) No example of this type in southern Arizona. Every large basin has at least a few exposures of volcanic rocks around its perimeter. Salt River valley, centering on Phoenix, is one of the largest in the region and perhaps has the fewest volcanic exposures along its margins. No wells in the central part of the basin have reached bedrock, although many wells are as much as 700 meters deep. Nonetheless, the possibility of buried volcanic flows at greater depths is geologically sound, and if volcanic flows are encountered, they may be expected to have water-bearing characteristics that are determined by the degree of fracturing and the degree of hydraulic continuity with the overlying alluvium.

"FORMATIONAL" PERMEABILITY AND TRANSMISSIBILITY

The nature of the deposition of volcanic flows results in a high degree of anisotropy of permeability. Voids and zones of brecciation tend to be aligned both parallel and transverse to the direction of flow. However, the directions of flows in many places depart widely from the basic radial pattern around a volcanic center or from the basic linear pattern of down a valley or across a plain. Transmissibilities of sequences of flows also vary considerably within short distances, because of the general thinning of volcanic piles away from their sources and the intercalation of deposits of sedimentary, pyroclastic, and much less permeable extrusive rocks. Furthermore, in many places, younger dikes and faults may block off large volumes of the sequences of flows into compartments, which have little or no hydraulic continuity. In spite of wide local variations in permeability, transmissibility, and hydraulic continuity, large areas of fractured volcanic flows in southern Arizona may be considered to have reasonably uniform "formational" permeabilities and transmissibilities. These formational hydraulic characteristics are the "average" of great local differences of lithologic and hydraulic characteristics, and it is not only useful but necessary to consider the water-bearing potentialities of volcanic rocks in terms of formational rather than local characteristics.

The "formational" permeabilities of the volcanic rocks discussed in this paper, and their abilities to transmit water, seem to be generally high. Although no quantitative estimates of permeability can be made on the basis of local pumping tests, evaluations and estimates of permeability can be made on the basis of observations of surface characteristics and water-level configurations and from records of pumpage and water-table declines. The description and examples given here are no doubt of rocks whose permeabilities are higher than average, and equally favorable permeabilities cannot be expected everywhere fractured volcanic rocks are water-bearing.

The mountains along the western boundary of the Papago Indian Reservation (fig. 2) are made up mostly of fractured and brecciated andesitic flows. In these mountains, there are practically no secondary tributaries to the main stream channels, which are consequent on the dip slopes. Runoff after a rain is concentrated in the main channels and overland flow is minor. The rainfall apparently percolates downward almost immediately and moves along the top of less permeable zones to be discharged along the stream channels almost as immediately. After a storm, the volcanic rocks drain noticeably for only a few minutes or a few hours. Even reliable wet-weather springs and seeps are rare because the volcanic rocks apparently release the water as rapidly as they absorb it.
Movement of water through these volcanic rocks can be so rapid as to be seen and
heard. Workers at the “shaft-well” near Ajo (described in preceding section, item
B-2-c) report that the movement of water could be watched before the water level
dropped too far below the floor of the shaft; and in 1956, when the water level was 13
meters below the level of the floor of the shaft, the water in the well could be heard
gurgling merrily.

These observations suggest permeability as high as or higher than that of the alluvial
deposits of the intermontane basins, and, in some places the water tables in adjoining
valleys appear to be so concordant as to suggest that the volcanic mountains between
them are acting as conduits rather than barriers. In other places, the water table in
alluvial and volcanic rocks in the same valley appear to be concordant.

Concordant water tables on opposite sides of a range composed of volcanic rocks
occur in the southwestern part of the Papago Indian Reservation (fig. 2). The mountains
along the western boundary are made up mostly of fractured and brecciated andesitic
flows. These flows are interbedded with thinner units of less fractured volcanic deposits
and lenses of consolidated alluvium. The volcanic sequences rest on much less per-
meable bedrock composed of metamorphosed sediments, gneiss, and granite or quartz
monzonite. The less permeable bedrock units, in turn, make up most of a chain of
mountain ranges, which are roughly 50 kilometers east of the mountains along the
boundary. Between the two chains of mountains is a third chain of small ranges, com-
prised mostly of the Gu Vo Hills and the Mesquite Mountains. This third chain of
mountains is composed mostly of permeable andesitic flows. The two basins between
the three chains contain alluvium that is at least 210 meters thick where it has been
penetrated by wells. Although the two basins are nearly completely separated from each
other by the chain of mountains between them, the water table in their alluvial deposits
is almost concordant. In an area of about 1,200 square kilometers, the water table in
the period of 1956-1958 lay between altitudes of 450 and 475 meters and had east-west
and north-south gradients of about 5 and 1 meters per kilometer respectively. In the
absence of firm evidence for an effective barrier which may hold up the water levels,
it seems illogical to accept such a configuration of the water table, unless water were
able to move as freely through the rocks of the mountains between the valleys as it
did through the alluvium itself. The transmissibility of a saturated thickness of 200
to 300 meters of alluvium is on the order of 100 cubic meters per day per meter. In that
the saturated thickness of the flows in the Gu Vo Hills is estimated to be about 100
meters, it seems reasonable to assume that their formational permeability is at least
that of the adjacent alluvium.

An example of concordant water levels in volcanic and alluvial rocks is in Ajo
Valley. Wells drilled about 2 kilometers south (upgradient) and 2 kilometers north
of the “shaft well” penetrate alluvium to depths of 342 and 200 meters, respectively.
In contrast, the alluvium in the “shaft well” between them is only about 60 meters
thick. The gradient between the south and shaft wells is about 5 1/2 meters per kilometer
and that between the shaft and north wells is about 4 meters per kilometer. The general
concordance of gradients here again suggests a similarity between the permeability
of the alluvial and volcanic aquifers in this valley.

Additional indication of the permeability of the volcanic aquifer in Ajo Valley
is obtained from the pumpage records. These indicate that about 100,000,000 cubic
meters were pumped and that the water table declined about 13 meters between 1913
and 1956—or a yield of about 8,000,000 cubic meters of water per meter of water-table
decline. These data indicate a far greater yield than that from volcanic rocks underlying
Bonita Creek (item 3-b), where specific capacity was estimated to be the equivalent
of about 5 liters per minute per meter of drawdown (Heindl and McCullough, 1961),
or that from the volcanic rocks underlying Eagle Creek (item 3-b), whose “safe yield”
reportedly was calculated to be about 60 liters per second.

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These notes indicate both the high local potential fractured volcanic rocks have as local sources of water and the wide variability the same sequence may have in its water-bearing characteristics. Probably no amount of hydrologic, hydraulic, and statistical analysis of even much more information than we now have will preclude the drilling of “dry” holes within short distances of good producers or the drilling of a successful well after a discouraging number of failures. Nonetheless, certain types of information could aid greatly in providing a basis for locating test holes whose chances of success are favorable.

1. Mapping of patterns of alignments of voids, breccia, and fractures as a basis for determining direction of the flow of lava, and thus a part of the pattern of distribution of water-bearing characteristics.

2. Mapping of volcanic units—or sequences of similar units—on the basis of hydrologic rather than stratigraphic criteria; that is, mapping potential aquifers rather than formation.

3. Mapping the structural deformation and consequent or related erosion, particularly to identify evidence that will indicate the geometry of the deposits where they are buried beneath the alluvium of the basins.

4. Development of an integrated environmental history of deposition, deformation, and erosion of the potential volcanic aquifers. This is the basic hypothesis upon which projections and predictions are made.

5. Projection of patterns of distribution of permeability and transmissibility and the effects of structural deformations and erosion, as exposed in the hills and mountains, into the adjacent alluviated basins.

6. Use of available subsurface information to modify and refine projections of the geometry of the buried deposits and their water-bearing characteristics. Subsurface information should be interpreted in conjunction with the integrated history, which may be modified as subsurface data are accumulated.

7. Geophysical information should be used only after a thorough synthesis of surface and subsurface information.

8. Test holes, finally, are needed to substantiate predictions and projections and to provide firm data regarding the water-bearing characteristics and the quality of water. Evaluation of test holes should be made with due regard for the possibility that any one test hole may not be an adequate test of the “formational” hydraulic characteristics.

Use of a simplified version of this rationalized approach to exploration and evaluation of ground-water supplies in volcanic rocks has resulted recently in the development of successful water supplies for the villages of Kaka and Hotosan Vo on the Papago Indian Reservation. At both villages, the water was developed in volcanic rocks below moderate thicknesses of alluvium in basins where no hydrologic information, other than that deduced from the geologic features exposed in the adjacent mountains, was available within several kilometers. At both sites, bailing tests indicated a minimum yield of about 2 liters per second with no apparent drawdown, an amount sufficient for the domestic and stock requirements of each village. In both instances, the water levels in the volcanic rocks were concordant with those of the adjacent or nearby alluvial basins.
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