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Gravity and Fault Structures, Long Valley Caldera, California

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Abstract

The main and catastrophic phase of eruption in Long Valley occurred 0.73 m.y. ago with the eruption of over 600 km^3 of rhyolitic magma. Subsequent collapse of the roof rocks produced a caldera which is now elliptical in shape, 32 km east-west by 17 km north - south. The caldera, like other large Quarternary silicic ash-flow volcanoes that have been studied by various workers, has a nearly coincident Bouguer gravity low. Earlier interpretations of the gravity anomaly have attributed the entire anomaly to lower density rocks filling the collapsed structure. However, on the basis of many additional gravity stations and supporting subsurface data from several new holes, a much more complex and accurate picture has emerged of caldera structure. From a three-dimensional inversion of the residual Bouguer gravity data we can resolve discontinuities that seem to correlate with extensions of pre-caldera faults into the caldera and faults associated with the ring fracture. Some of these faults are believed related to the present-day hydrothermal upflow zone and the zone of youngest volcanic activity within the caldera.

Introduction

The Long Valley caldera in east-central California lies near the topographic margin of the Sierra Nevada batholith and the Basin-and-Range geomorphic province (Fig. 1). Scattered volcanism in the area began in the Pliocene and culminated in a major silicic ash-flow eruption about 0.73 m.y. ago when over 600 km^3 of ejected magma produced the Bishop Tuff (Bailey et al., 1976; Bailey, 1987). Collapse of the roof rocks over the evacuated magma chamber followed by volcanic resurgence has resulted in an elliptical caldera measuring 32 km east-west by 17 km north-south. Volcanism has continued up to the present; the youngest lava domes of the 45-km-long Inyo-Mono chain in the western part of the caldera are only 600 to 700 years old. On the basis of the ages of volcanism and drill hole results, some holes drilled to 6000 feet, the highest rock temperatures and the source of the thermal waters are in the western part of the caldera. The hydrology appears to be complex and is not fully understood (Sorey, 1987). The general picture shows that thermal waters (220-230 °C) ascend along major faults/fracture zones associated with the ring-fracture system of the west moat, and enter permeable zones within the Bishop Tuff and the overlying, post-caldera early rhyolites. The thermal waters then flow mainly to the east, mix with cold meteoric water, and emerge at a number of hot springs at the south and east margins of the resurgent dome. There is no evidence that any of the drill holes has intersected an upflow zone, but a model derived from the hydrogeology and a 3-D gravity interpretation shows evidence for faults that might be principal conduits for the thermal waters.

Gravity Inversion

The gravity set used for the 3-D modeling consists of 2026 station readings obtained from the U.S.G.S., and another 473 station readings that were made available to us by Unocal Geothermal. The resulting residual

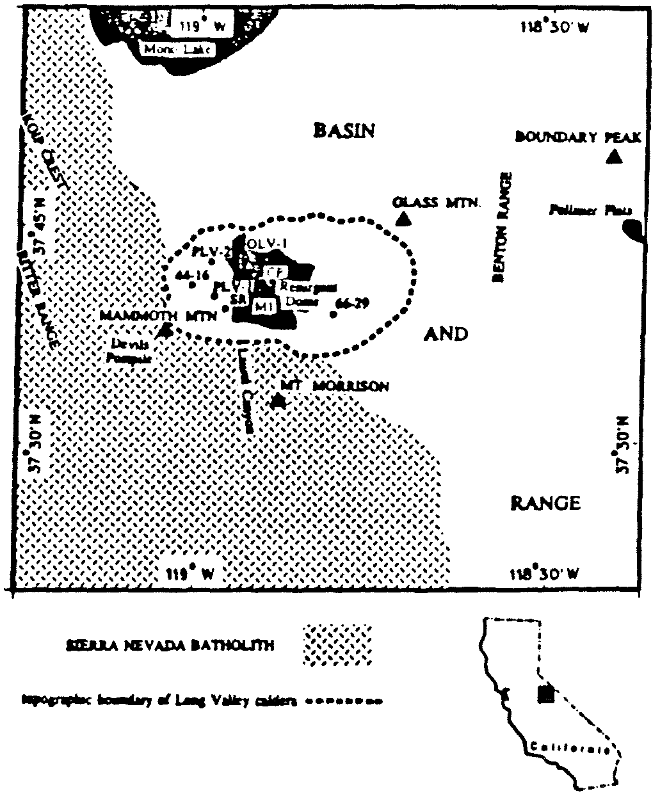

Figure 1. Location map of the Long Valley caldera showing some of the principal exploration and hydrogeologic test holes.

Bouguer anomaly (Fig. 2) was obtained after a regional correction to the data was made by applying the "best-fitting" Airy-Heiskanen isostatic model (Carle, 1987). Because crustal amd mantle densities are not likely to be uniform and the crust may not be entirely compensated, the isostatic connection is at best a good first approximation for the regional effect.

Similar to the gravity anomalies observed over other young, ash-flow volcanic calderas, Long Valley exhibits a gravity low whose margin closely matches the topographic boundary shown as the dashed line in Fig. 2. The low of up to -48 mGal is attributed to the lower densities of the caldera-filling volcanics and sediments. Kane et al. (1976) and Abers (1985) modeled the intracaldera gravity variations by means of 1-D and 2-D methods, respectively, and attributed the gravity changes entirely to variations in the thickness of the caldera fill. The shape of the caldera was generally defined by seismic refraction profiles (Hill et al., 1985).

In this paper we discuss an attempt to model the residual Bouguer gravity data three-dimensionally to account for the complexities in structure and distribution of rock types. To do this the earth was represented as a grid of rectangular prisms, each measuring 1.4 km on a side and extending from the mean surface elevation to a reference depth. Each prism is composed of a number of lithologic units based on known geology (Bailey and Koeppen, 1977). Each unit is assigned a constant density based on published bulk densities determined either from direct measurements on surface samples and cores or indirectly from well logs (Abers, 1985). To be determined are the thicknesses, $t_{i,j,k}$, of unit k at all grid rectangles, i,j (Fig. 3). The lateral extent of unit k is described by non-zero values of a 2-D array of the parameter $t_{i,j,k}$, and a file for each unit was created on the basis of drill hole lithologies and the surface geology (Bailey and Koeppen, 1977). Fortunately, we had lithologic information for all the holes shown in Fig.1, except OLV-1. These data provided constraints for both the lateral extent of some units and the thicknesses of specific units within the grid blocks where the holes are located. The grid rectangle size of 1.4 km, which is the lateral resolution of the model, is too coarse to resolve small features. However, grid size is a reasonable compromise between resolution, accuracy and computer time. The grid size is large enough so that at least one gravity station lies within most rectangles, yet small enough to resolve major caldera features.

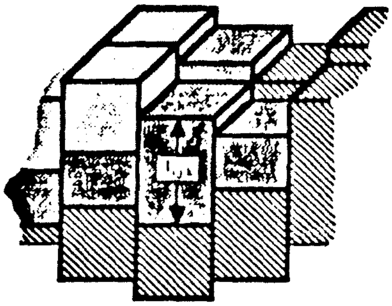

Figure 3. Simplified diagram of model geometry.

The vertical gravitational field on the surface at the center of each prism is calculated by summing the contributions from every element in the model. To reduce the computational expense by at least a factor of six while maintaining a level of computational accuracy well within the limits of uncertainty of model parameters, the prismatic elements are approximated by cylindrical elements (Kane, 1962). Edge approximation calculations are

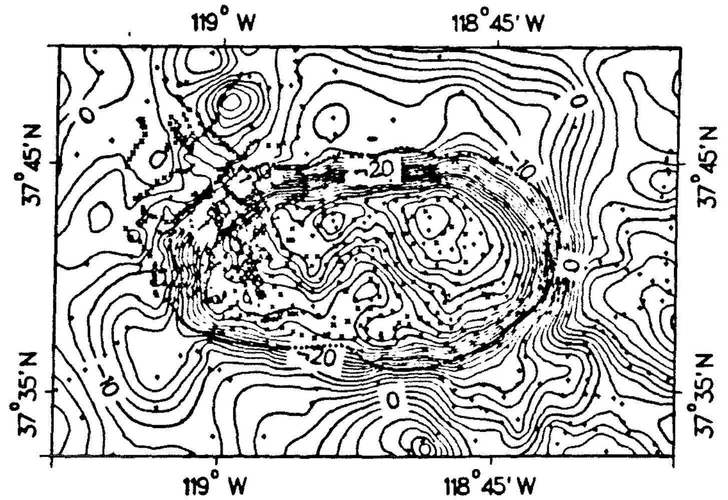

Figure 2. Residual Bouguer gravity map used in the 3-D inversion. The contour interval is 2mGal. +'s and x's denote U.S.G.S. and Unocal Geothermal gravity stations, respectively. The dashed line is the topographic margin of the caldera.

needed to account for mass variations outside the grid boundaries. Units that abut the outer grid boundary are assumed to extend to infinity with the same thickness as in the boundary elements of the model. A line mass approximation was used to calculate these effects, and it was effective in repressing instabilities at the edge of the modeled area. The edge approximation contributes less than 1 mGal at points within the caldera.

Determination of the unit thicknesses was done following an iterative approach introduced by Cordell and Henderson (1968), but modified to account for multiple density units and edge effects. After an initial model is created, based as much as possible on known geology, the gravity field, g_{calcij}, is calculated at each grid point. Because the calculated and observed values will not agree, the next step is to adjust unit thicknesses to force a convergence. For a single density-unit Cordell and Henderson (1968) proposed that a new unit thickness be found as follows:

$$t'_{ij} = t_{ij} \frac{g_{obsij}}{g_{calcij}} ,$$

where g_{obsij} and g_{calcij} are the observed and calculated values at grid point ij. After this calculation is made at all grid points, the gravitational effect is recalculated and the whole process is repeated. After 3 to 10 of these iterations convergence is obtained to better than 1 mGal at every grid point. In the case of multiple units the process is modified so that two or more unit thicknesses may be adjusted at each iteration. Usually only a few units are iterated at a time, and we normally begin the iteration process by choosing the "key" units; those that have a large density contrast and/or are expected to be thick and therefore have a large effect on the gravity. After each cycle of the iteration process we stop to display unit thicknesses and to make sure they are geologically plausible before proceeding.

Caldera Structure

Most of the residual Bouguer anomaly can be accounted for by the Bishop Tuff, early rhyolite flows and tuffs, and lake sediments. The other pre-collapse and post-collapse units within the caldera are thin or not extensive. The total thickness of supra-basement rocks are shown in Fig. 4. A trench-like thickening of caldera fill can be traced continuously around and within the caldera margin. There is also a strong asymmetry in the caldera floor. Caldera fill in the north and east moat areas is up to 2.8 km. This feature has been recognized for some time and explanations have been proposed: (1) there was a more complete evacuation of the magma chamber beneath the east moat (Lachenbruch et al. 1976), and (2) the east moat was a topographically lower area at the time of the Bishop Tuff eruption (Bailey, 1987).

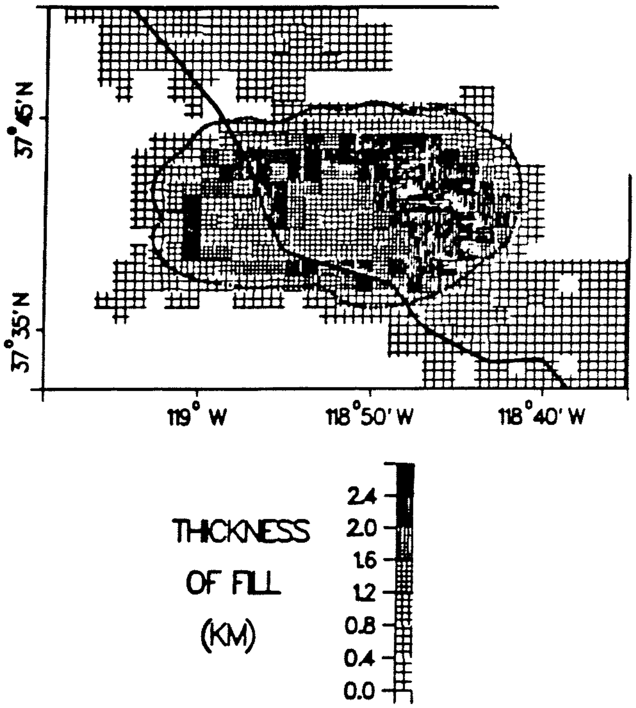

Figure 4. Thickness of all caldera fill, including pre-caldera volcanics. The diagonal line across the figure is highway 395.

The trench-like thickening within the caldera is difficult to explain. No models for caldera development have been found in the literature that predict this type of structure. Carle (1987) speculated that the feature may be structural or may be caused by highly fractured and lower density rocks extending into basement and associated with an inner ring-fracture zone.

To examine the "ring trench" in the light of additional geologic data, we show in Fig. 5 the major northwest-trending faults (Bailey and Koeppen, 1977) and their postulated concealed extensions (Bailey, 1987). The two major frontal faults of the Sierra Nevada, the Hilton Creek (HC) and the Hartley Springs (HS), run into the caldera from the south and north, respectively, and cannot be positively identified on the opposite rim of the caldera. The Hilton Creek fault, a reactivated Paleozoic or Mesozoic structure with a strong normal component, seems to die out and splinter within the caldera. The pre-caldera terrain probably consisted of a depressed area east of the fault and mountainous terrain to the west. The ancient topography is a possible reason for the asymmetric structure of the caldera.

The Hartley Springs fault enters the caldera and merges with the north-south-trending Inyo-Mono chain of rhyolitic lava domes and connecting dikes that are the youngest volcanic events recognized in the caldera (600 - 700 y). Within the caldera, the extension of the Hartley Springs fault also correlates with both a mapped graben and the ring-trench segment of the west moat.

The Fern Lake-Silver Lake (FL-SL) fault zone enters the caldera at the western rim and cannot be positively traced further. However, it has been conjectured that

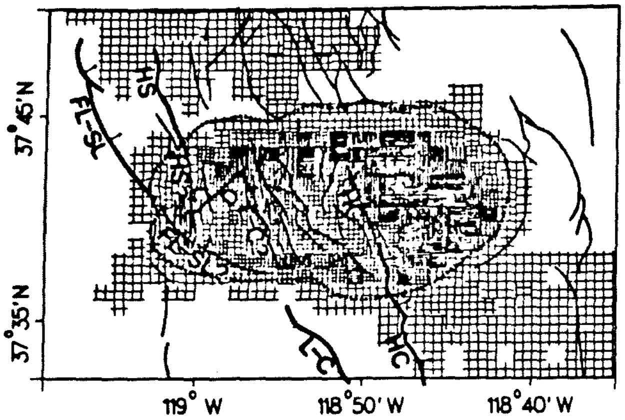

Figure 5. The same as Fig. 4 but with the addition of recognized faults from Bailey and Koeppen (1977). The heaviest solid lines are the major northwest-trending Sierran faults, dashed where extended into the caldera. FL-SL is the Fern Lake-Silver Lake fault, HS is the Hartley Spring fault, HC is the Hilton Creek fault, L-C is the Laurel-Convict fault, and D is the Discovery fault.

the FL-SL fault may be related to the Laurel-Convict (L-C) fault in the Sierran block to the south (Bailey, 1987). The connecting transform fault segment between the FL-SL and L-C faults correlates with the ring trench in the southwest corner of the caldera and it also correlates with part of the seismically active area of the south moat where the dominant motion is strike-slip. Therefore, the FL-SL and L-C faults may be structurally related and may have controlled a part of caldera development. The Discovery fault (D) is a newly recognized fault (Suemnicht and Varga, 1987) that trends northeasterly. It too seems to correlate to a segment of the ring trench. The results of the 3-D inversion plotted as 2-D cross-sections across the caldera clearly show the ring trench. Fig. 6. is an east-west cross-section through the south moat and passing through hole M-1 at Casa Diablo Hot Springs. The FL-SL fault segment cuts the section at the major vertical discontinuity seen at the western margin of the caldera. At the eastern margin of the caldera, on the other hand, there appears a set of down-stepping faults into the ring trench. There is no known major northwest-trending pre-caldera fault here. Between the two trenches the caldera floor is bowed up into a broad arch.

Fig. 7 is another east-west cross-section. This one goes through the center of the caldera, passing through boreholes 44-16 and CP, both of which bottomed in pre-caldera basement rocks. On this cross-section the ring-trench of the west moat correlates with a mapped graben. The large thickness of the youngest volcanics intersected by hole 44-16 and the presence of visible fault scarps suggests that the graben structure has been an active zone up to the present time. In particular, the large thickness of Quaternary basalts and andesites that erupted around 60,000 years ago and the very young rhyolitic eruptions of the Inyo Craters suggest a zone of east-west extension which has provided conduits for the ascending magmas.

Fig. 8 is a semi-schematic geologic cross-section of the western part of the caldera and is controlled by information from holes 44-16, PLV-1, SR, and M-1 (Benoit, 1984; Suemnicht, 1987; Wollenberg et al., 1987). The ring-trench of the west moat may be clearly seen in this depiction. We can only speculate at this time how these faults control ascending thermal fluids. It is possible that the main fluid conduits lie to the southwest of this section and near the intersection of the Hartley Springs and Fern Lake - Silver Lake faults.

Conclusions

A 3-D inversion of 2499 gravity readings in and around the Long Valley caldera was carried out to determine caldera structure. The inversion shows a highly asymmetric caldera containing 2 to 2.8 km of caldera fill east of the Hilton Creek fault zone. Within the caldera there is a ring trench, a pronounced thickening of the caldera fill, in a nearly continuous concentric zone 2 to 3 km within the topographic margin of the caldera.

Although there is evidence that the ring trench is related to a system of faults, how the trench developed is not clear. It may have been caused by the following mechanisms: (1) differential collapse along the ring-fracture zone in response to ejection of pre-caldera rocks accompanying the Bishop Tuff eruption, and (2) late-stage magmatic resurgence, upward arching of the caldera floor and crustal extension followed by detumescence and further settling of the caldera floor along the ring-fracture zone.

In the southwest and western part of the caldera the ring trench correlates to extensions of major faults that existed long before the caldera developed. In the west moat the trench correlates with a mapped graben that has been a recently active structure and a conduit for magma feeding the Inyo Craters chain of rhyolitic domes. The Fern Lake - Silver Lake, Hartley Springs and Laurel-Convict faults probably controlled caldera development to some extent. There is evidence from geology that segments of these faults, particularly at certain fault intersections, may provide the conduits for ascending thermal fluids that have been found now in several holes and which are being produced at the Mammoth-Pacific geothermal plant located at Casa Diablo Hot Springs.

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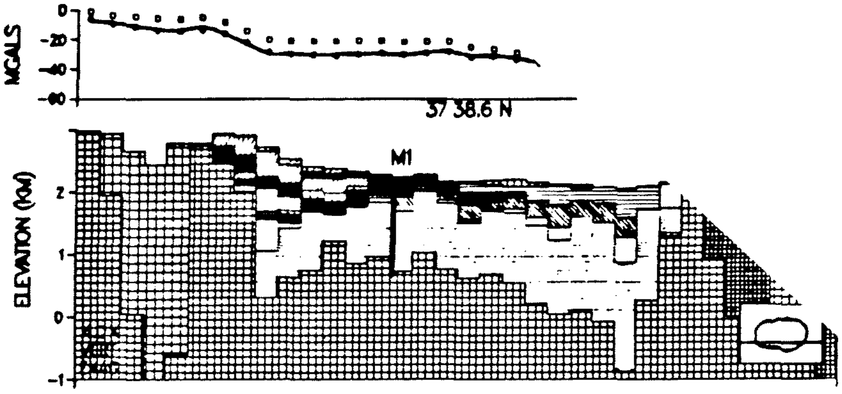

Figure 6. An east-west geologic model based on the gravity through the south moat and drill hole M-1. See insert for location of the cross-section.

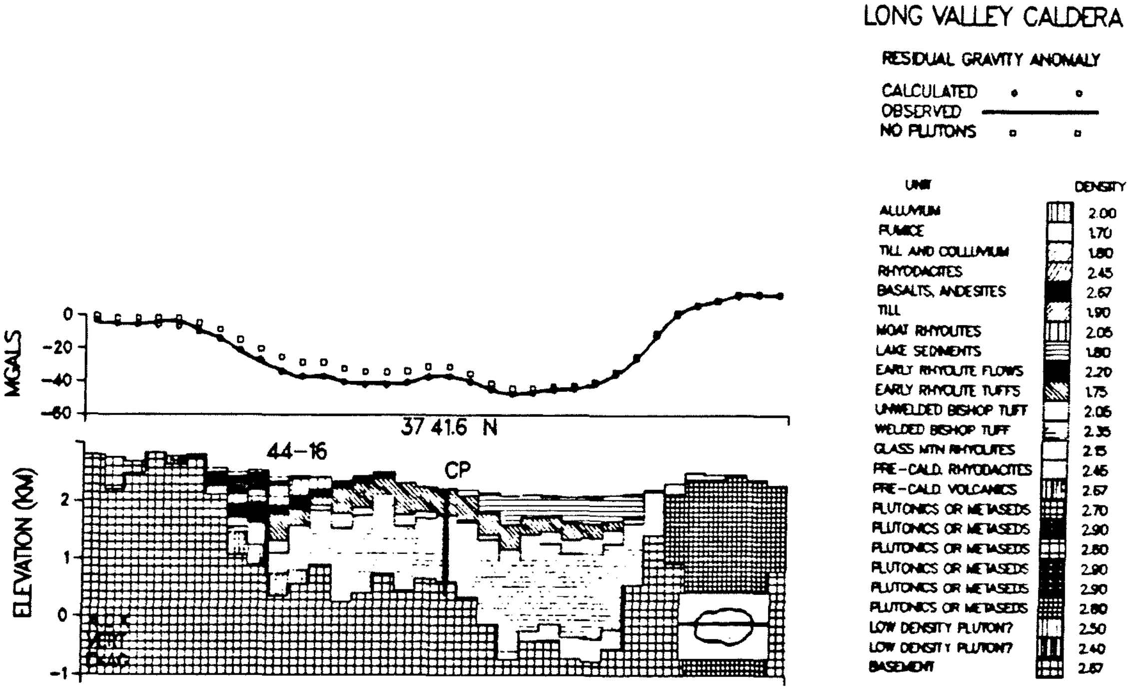

Figure 7. An east-west geologic model through the central part of the caldera and drill holes 44-16 and CP.

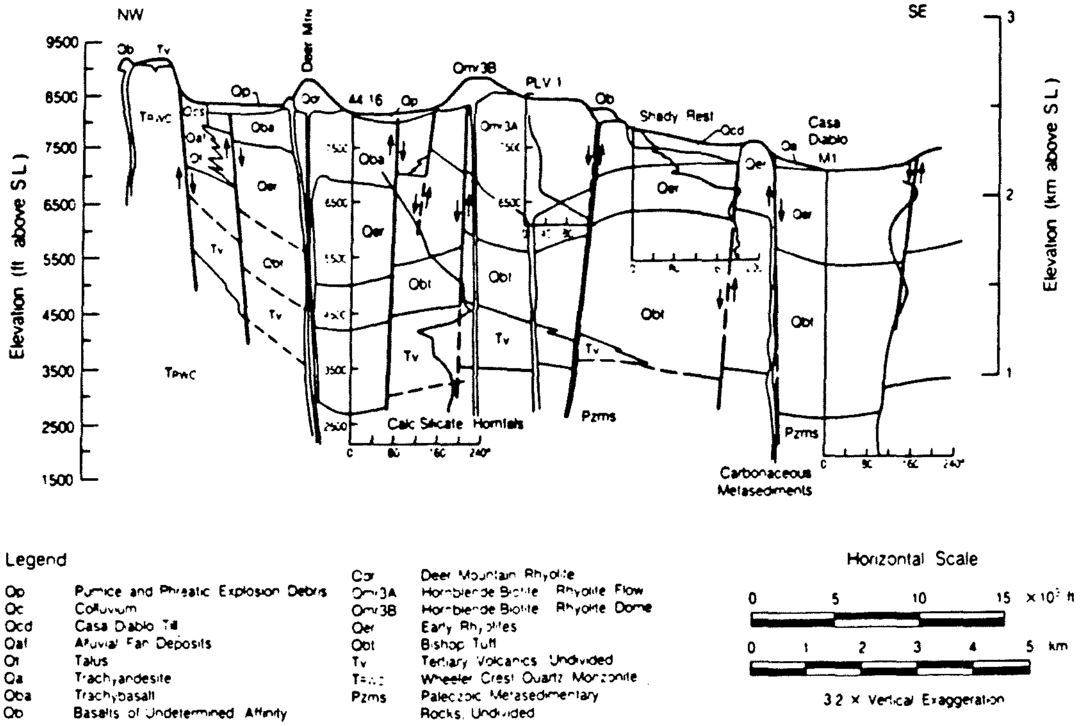

Figure 8. Hydrologic cross-section running NW-SE across the moat area.

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