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RELATION OF FOSSIL LANDSLIDES TO GEOLOGIC STRUCTURE, CANELO HILLS, ARIZONA

By

Phillip Paul Denney
Standard Oil Company of Texas

INTRODUCTION

The Canelo Hills of southern Arizona (Figure 1) exhibit a peculiar sedimentary feature that has previously been interpreted as a tectonic structure. This feature consists of large allochthonous slabs and boulders of Paleozoic limestone contained in a volcanic-clastic rock sequence of Triassic-Jurassic age. Erosion of this formation, known as the Canelo Hills Volcanics, has left the resistant limestone blocks isolated from in-situ Paleozoic beds. In this position these blocks have previously been interpreted as erosional remnants of a thrust sheet.

This paper describes the structural geology of the central Canelo Hills. The relationship of the Canelo Hills Volcanics to the Paleozoic section is discussed and an alternative hypothesis to the thrust sheets of others is presented to account for the unamalous appearing contact.

The original work for this paper was done as an M.S. thesis under the direction of Dr. W. D. Pye, formerly with the University of Arizona. In addition to Dr. Pye, I would like to thank Dr. D. L. Bryant and Al Ried for the identification of fossils. More specifically, I wish to thank Dr. Andrew Nevin who read and critized portions of the preliminary manuscript. Finally, I offer my sincere thanks to my wife, Dorene. Her efforts and encouragement made the earlier thesis possible.

PREVIOUS WORK

The first detailed work concerning the Canelo Hills was published in 1947 by Feth. Feth mapped in the area of Mount Hughes at the northern end of the Canelo Hills. In this area he described what he believed to be a block of Permian limestone thrust to the southwest over Cretaceous(?) sedimentary and Tertiary volcanic rocks.

Cetinay (1967) mapped a part of the Canelo Hills immediately to the north of the area of this report. He describes a thrust of Paleozoic strata towards the northeast onto "Cretaceous" (?) rocks.

Hayes, Simons, and Raup (1965, 1966), have worked in several areas of the Canelo Hills. They first recognized the exotic nature of the blocks within the Canelo Hills Volcanics.

PALEOZOIC STRATIGRAPHY

The ages of the rocks exposed in the central Canelo Hills range from Late Cambrian through Quaternary. With the exception of the Ordovician and Silurian Periods, the Paleozoic portion of these rocks includes representatives of every period from Cambrian through Permian.

The oldest formation exposed is the Upper Cambrian Abrigo Limestone which has an exposed thickness of 158 feet. Overlying the Abrigo Limestone in ascending order with measured thicknesses given are the Devonian Martin Limestone (278 feet), Lower Mississippian Escabrosa Limestone (516 feet), Pennsylvanian Horquilla Limestone, Permo-Pennsylvanian Earp Formation, Permian Colina Limestone, and locally, the Permian Scherrer Formation. All the Paleozoic strata may be readily correlated with well-established sedimentary sections elsewhere in southeastern Arizona on the basis of lithology, faunal content and wide-spread marker beds.

The succession of two wide-spread marker beds is locally indispensible for proving structural relationships in the Canelo Hills. This succession consists of a gray limestone-pebble conglomerate, eight feet thick, followed by five - ten feet of red and gray chert-pebble conglomerate set in a brown limestone matrix. Approximately ten feet of light-colored, sandy, medium-bedded limestone separates the two conglomerate beds.

Rea, 1967, described the red chert-pebble conglomerate at other localities in southeastern Arizona. He concluded that it is a single, distinctive, probably isochronous marker bed in southeastern Arizona.

MESOZOIC STRATIGRAPHY

In the Canelo Hills, the Paleozoic rocks are overlain by the Canelo Hills Volcanics. The Canelo Hills Volcanics are a group of interbedded volcanic and sedimentary rocks recently described by Hayes, Simons, and Raup (1965).

The main ridge of the Canelo Hills is a strike ridge comprised of the Canelo Hills Volcanics. Elsewhere in the study area, these rocks are exposed in the streambed at Rattlesnake Dam and to the north in sections 5 and 6. In sections 5 and 6, the Canelo Hills Volcanics are in fault contact with Paleozoic strata on the west and the Cretaceous (?) Bisbee Group on the east. The exposure of the Canelo Hills Volcanics along the main ridge has a regional dip of 23° to the southwest. This value is about 12° less than the dip of the Paleozoic section that the Canelo Hills Volcanics are faulted against.

Hayes (and others, 1965), have subdivided the Canelo Hills Volcanics into three major units, i.e., (1) a basal conglomerate composed of coarse limestone and volcanic fragments with subordinate arkosic sandstone and rhyolite; (2) an intermediate unit of rhyolite with a few thin, interbedded, red, welded-tuff beds; (3) a thick sequence of welded tuff. Hayes, et. al., estimate the three units to have a combined thickness of 9,400 feet. Within the area of this study, only the lower two subdivisions are present. They have a combined thickness of 2,179 feet.

Along state highway 83, the Lower Mesozoic section has been downdropped along a major fault, thus exposing the intermediate unit of rhyolite. In the area of Double Tank, the basal unit is overlain by several hundred feet of rhyolite exhibiting weakly developed flow structure. This rhyolite is believed to represent the lower beds of the intermediate member. The upper welded-tuff member of the Canelo Hills Volcanics was not studied, but was observed southeast of Arizona Highway 83 in the west half of section 17.

An outstanding characteristic of the lower two members of the Canelo Hills Volcanics is the presence of brecciated blocks of Upper Paleozoic limestone (or sandstone enclosed by beds of rhyolite or conglomerate of Mesozoic age. Individual blocks, possibly ranging in length up to several thousand feet, have remained together as deranged bedding slabs even though brecciated during movement. Smaller blocks, those 20 feet or so in diameter, show healing of brecciated fragments by secondary calcite or thin stringers of red arkosic sandstone.

Although the bedding is disturbed, it is generally still evident in the larger exotic blocks. In these blocks the bedding shows dips similar to the enclosing beds of the Canelo Hills Volcanics.

Silicified fossils allow dating of the rocks comprising some of the exotic blocks. It was determined that the blocks have been derived from the Concha Limestone, Scherrer Formation, and the Colina Limestone. In addition, an occurrence of conglomerate and red sandstone similar to those in the lower member of the Canelo Hills Volcanics was found in the form of a block "attached" to a limestone block. This assemblege occurred in the intermediate rhyolite member of the Canelo Hills Volcanics.

The exotic blocks may apparently occur at any stratigraphic level in the basal or intermediate members of the Canelo Hills Volcanics. This is illustrated (Figure 1) in the SE 1/4 of section 18 and the NE 1/4 of section 20, where several exotic blocks are juxapositioned against each other. Good definition of the actual position of these particular blocks is obscured by the changing strike in the area, but they range upwards in the basal conglomerate member of the Canelo Hills Volcanics. Nearer to the state highway, in sections 19 and 24, other blocks are exposed within the intermediate member of the Canelo Hills Volcanics. In section 17, two other blocks were found. The one nearer the center of section 17 is overlain by welded tuff, probably of the upper welded tuff member of the Canelo Hills Volcanics.

The streambed in the NE 1/4 of section 24 provides the best exposure in the area of the contact of an exotic block with the enclosing conglomerates. The dip of the conglomerates can easily be determined by walking up the gully. The contact of the block with the rocks beneath can be seen to "vee" upstream in the same direction as the dipping Canelo Hills Volcanics. On the small hilltop, 250 yards southeast of Double Tank, this exotic block is itself overlain by rhyolite and conglomerate of the Canelo Hills Volcanics.

The Canelo Hills Volcanics are the first sedimentary and volcanic rocks found in southern Arizona that can be dated with certainty as younger than early Permian and older than early Cretaceous (Hayes, Simons, and Raup, 1965). The inclusion of exotic blocks within the lower and intermediate members proves

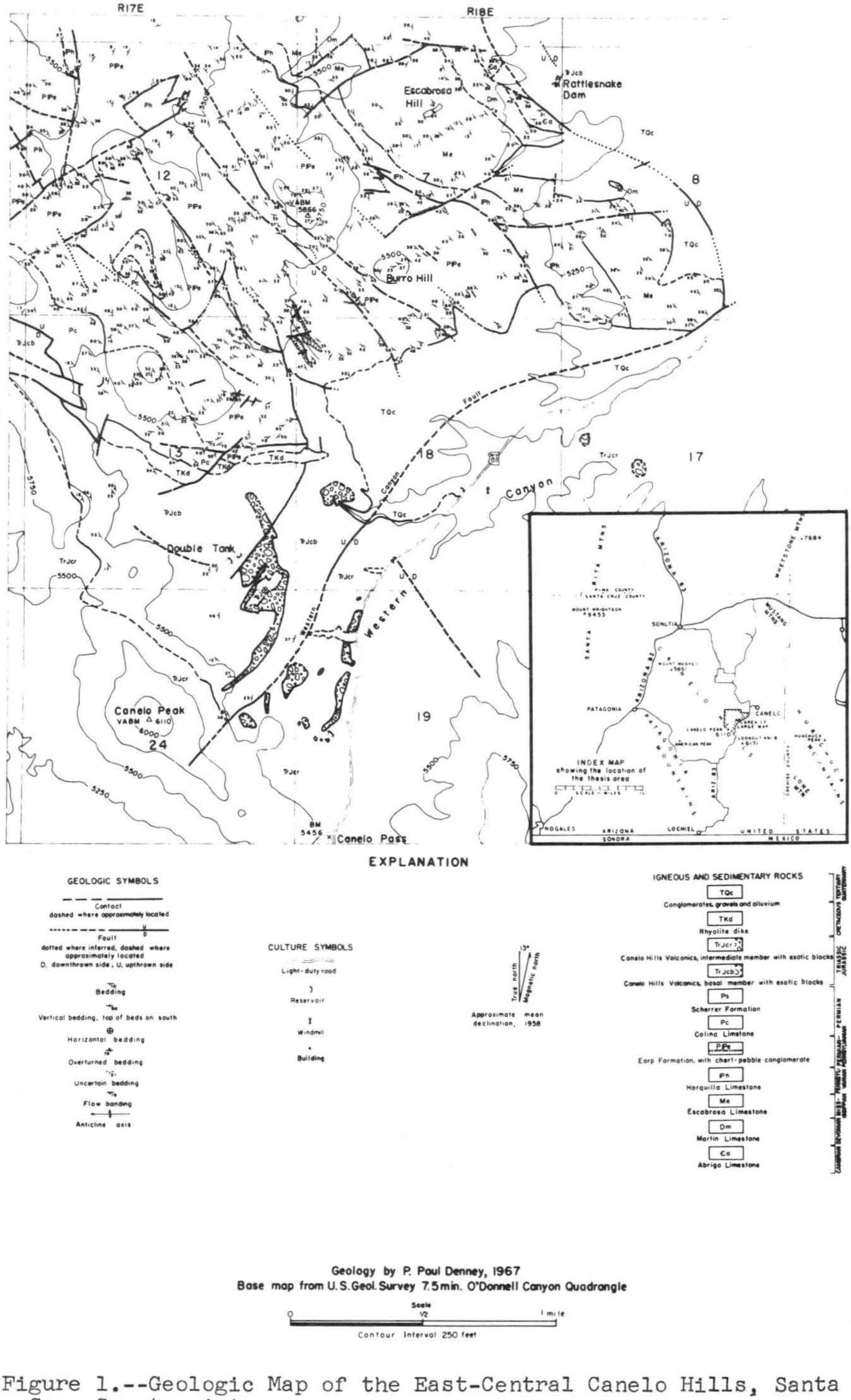

Figure 1.--Geologic Map of the East-Central Canelo Hills, Santa Cruz County, Arizona.

these members to be younger than the Paleozoic blocks they contain. At Lone Mountain, Hayes (and others, 1965, p. 4) describes the upper contact of the welded-tuff member with an overlying conglomerate that they correlate with the Bisbee Group (Early Cretaceous). They conclude that the welded-tuff is pre-Cretaceous and assign the Canelo Hills Volcanics to the Triassic-Jurrassic Systems. Their conclusion is substantiated by a potassium-argon isotope age determination of biotite from the welded tuff of 173 ± 7 million years. This places the welded tuff in the Late Triassic or Early Jurassic.

CANELO HILLS BASIN

No fossils have been found in the Canelo Hills Volcanics; however, small scale cross-bedding and good sorting in some beds of the basal member imply deposition by water. The angularity and size of fragments in the conglomerates suggest rapid deposition and short transportation without significant reworking of material. The presence of exotic blocks probably resulting from gravity slumps or landslides, suggests that the paleotopography was oversteepened. The distribution of blocks throughout the lower two members of the Volcanics implies that periodic uplifts, rather than a single catastrophic event, occurred from which the exotic blocks were derived.

Inferences, drawn on the basis of deposits reported in nearby area, can be made concerning the geometry of the Triassic-Jurassic basin. Figure 2 presents a proposed correlation with the northern Canelo Hills (Feth, 1947); Patagonia Mountains (Baker, 1962; north Huachuca Mountains (Alexis, 1949); central Huachuca Mountains (Weber, 1950); and the southern Canelo Hills (Hayes, Simons, and Raup, 1965).

Figure 2 reveals a thick section of limestone debris, with minor volcanic conglomerate, in the Huachuca Mountains. According to the proposed correlations, both the lower limestone conglomerate and the overlying clastic section thin toward the west and north. Thus, the source of the Canelo Redbeds of Feth; the Corral Canyon Formation of Baker; and the lower member of the Canelo Hills Volcanics, less the volcanic flows, was probably east of the Huachuca Mountains.

The volcanic activity that is represented by the rhyolite flows and tuffs in the southern Canelo Hills and the Patagonia Mountains appears to have originated south of these two localities. This conclusion is based on the absence of rhyolite and rhyolite tuff in the northern Canelo Hills and the Huachuca Mountains. In the area mapped, these volcanic rocks interfinger with the consolidated limestone debris that poured in from the east.

In the northern Canelo Hills finer-grained sandstones, pebbly-conglomerates and thin limestones suggest that this locale was distant from the source of the clastic material. Exotic blocks, observed on a reconnaissance visit, are also considerably smaller at this locale. Blocks composed of Concha (?) Limestone were mapped in the NW 1/4 of section 3, T21S R19E, and the SE 1/4 section of 33, T20S R19E. The largest of three blocks in this area measures approximately 300 feet in outcrop length.

Differences between the intermediate rhyolite member of the Canelo Hills Volcanics and the lower basic lava flows of the

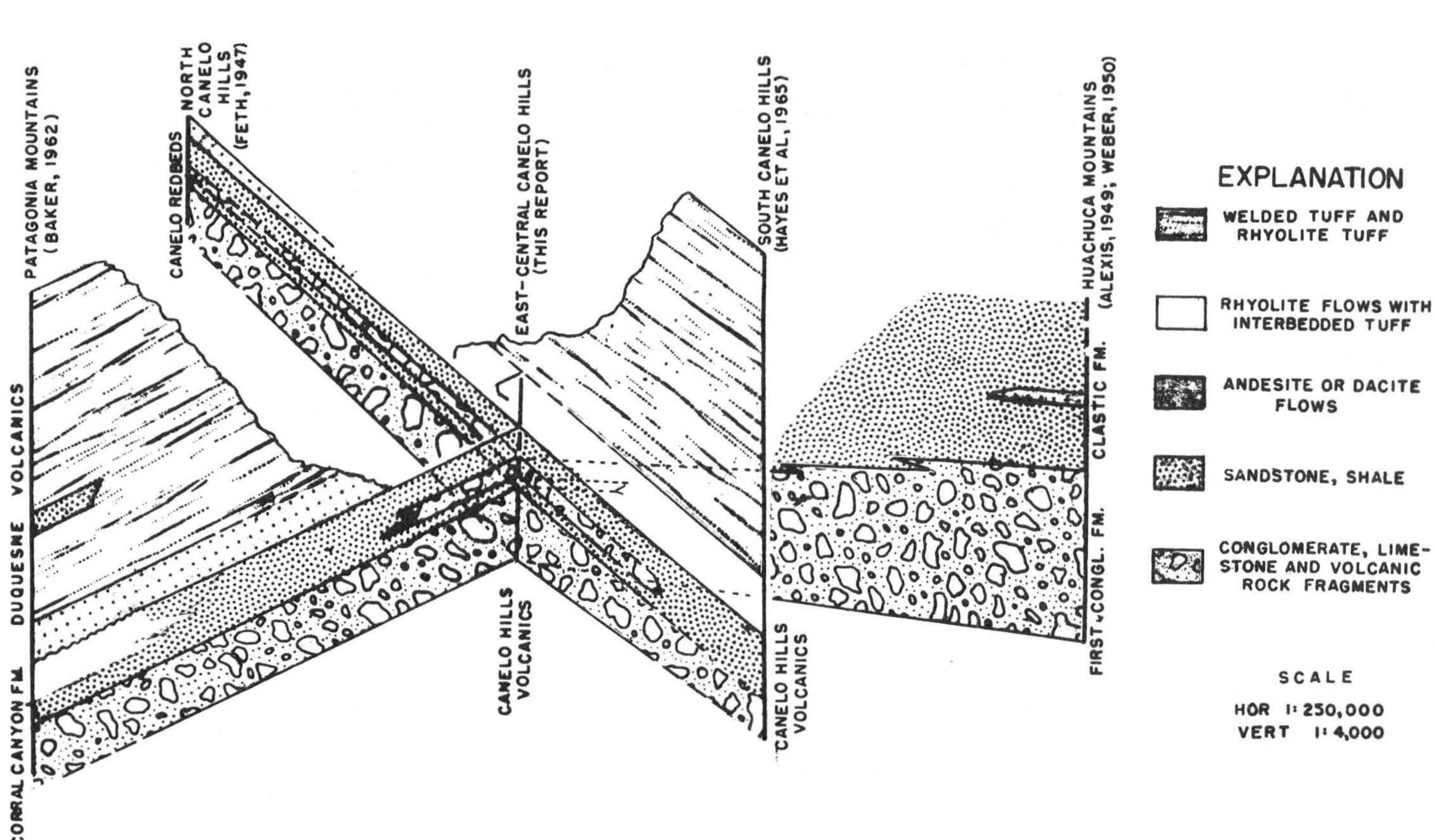

Figure 2.--Proposed Correlation of the Canelo Hills Volcanics Group.

Duguesne Volcanics in the Patagonia Mountains and the northern Canelo Hills may be explained in several ways. These rocks may have had different sources, but are still time equivalents; they may be differentiation lavas with a comagnetic source; or the attempted correlation may be faulty.

On the basis of Figure 2, it is concluded that the Triassic-Jurassic Canelo Hills Basin opened and deepened towards the north. At least two source areas were active during this time; a highland east of the present-day Huachuca Mountains supplied coarse limestone debris, while volcanic material was added from the southwest.

CRETACEOUS SYSTEM - BISBEE GROUP

The Bisbee Group is not present within the immediate area studied. However, in sections 5 and 6, T22S, R18E just north of the area of Figure 1, a conglomerate sandstone shale sequence is present. These rocks are assigned, on the basic of lithology, to the lower portion of the Bisbee Group. In this area the Bisbee Group is in fault contact with the Canelo Hills Volcanics. The contact was not mapped, but can be readily distinguished by differing lithology.

The Bisbee Group conglomerates are predominantly gray and contain only small amounts of limestone pebbles. Typically, the conglomerates consist of a high proportion of coarse-grained intrusive rock fragments with much smaller amounts of volcanic and limestone pebbles. In comparison, the basal Canelo Hills Volcanics contain a high percentage of limestone and volcanic fragments with an absence of intrusive rock. The predominant color is red. The sandstone in the Bisbee Group is coarse grained, poorly-sorted arkose. The color of this rock and the interbedded shales is usually gray to white. Best known nearby exposures of the Bisbee Group are one mile east of the town of Canelo. Wherever observed in this area, the Bisbee Group is the youngest strata involved in structural deformation.

STRUCTURAL GEOLOGY

The Canelo Hills comprise a large fault block tilted to the southwest. Cross-faulting of this large block allows for its division into three blocks differentiated by the relative amount of displacement. This paper is primarily concerned with the southern portion of the central Canelo Hills block. Observations in this area find no evidence of the compressional features that have been described in other portions of the Canelo Hills. Instead, an alternative hypothesis is presented to account for the anamalous Paleozoic-Mesozoic contact.

STRIKE FAULTS

The predominant geologic structures in the area are faults that parallel bedding. These "strike faults" all show normal displacement. Some strike faults have created a series of steps, down to the northeast, lowering the scarp ridge of the southwestward dipping central Canelo Hills block. This situation, combined with today's north-eastward dipping erosion surface, imposes duplicated stratigraphic sequences across the area mapped.

Actual exposures of the "step" or the northeastward dipping strike faults are rare, the best being in the gully southwest of Burro Hill (Figure 1). At this locality, drag folding on the upthrown side of the fault has rotated the beds into the fault producing a minor syncline. Also present is a duplicated section of the Earp chert-pebble conglomerate on either side of the fault.

Throughout the area of Figure 1, northeast dipping strike faults were directly associated with drag folding and duplicated conglomerate beds. Therefore, these features were considered valid criteria for extending faults along strike where other readily observable evidence was lacking. Those strike faults dipping southwestward are more apparent in the field since they involve a loss of section, as well as minor drag folding.

The presence of strike faults, in particular the northeast-dipping step faults, is emphasized by the apparent thickness of the Earp Formation. The outcrop of the Earp Formation measures 7,000 feet in width; the regional dip is 35°. If unfaulted, this incomplete section of the Earp Formation would represent a true thickness of 4,000 feet. Rea and Bryant, 1968, measured a complete section of the Earp Formation in the nearby Patagonia Mountains of only 473 feet, a thickness probably representative of the true section in the Canelo Hills.

No overturned folds were found throughout the area involved in this report. Actually, the only folding anywhere within this area, other than the minor drag folds, consisted of one small anticline. This feature is located in the NW 1/4 of section 18. It has a width of 250 feet and an amplitude of 75 feet. Four step faults are known to exist, however. In addition, two others are strongly suspected. These faults, as explained at the beginning of this section, account for the apparent overthickening of the Earp Formation. These step faults and another separating the Abrigo Limestone from Tertiary-Quaternany gravels, all have a displacement exceeding 500 feet. They dip 65° - 90° towards the northeast.

Two other strike faults are present. Both are normal faults dipping towards the southwest. One of these faults follows the valley between Burro Hill and Escabrosa Hill (author's designation) trending NW-SE (Figure 1). Displacement on this fault is such that the Earp chert-pebble conglomerate is downdropped against the lower Horquilla Limestone. Comparison of measured thicknesses of the Earp Formation and the Horquilla Limestone in this area with surrounding areas suggests a stratigraphic separation of 1,400 feet for this fault.

The second of these two large strike faults separates the Permian Colina Limestone from the Mesozoic deposits making up the main ridge of the Canelo Hills. In the south half of section 13, this fault has been intruded by a rhyolite dike along part of its length. This fault has an estimated 1,175 feet of throw, based on that amount of Permian strata known to exist in the Patagonia Mountains, but missing in the central Canelo Hills. However, part of the estimated amount of throw may be due to post-Permian erosion.

LATE NORTHEAST STRIKING FAULTS

Northeast striking faults are numerous but generally of small magnitude. Locally, however, the combined effect of these faults with the strike faults is to produce the small horst structures in section 12.

One fault of the northeast trend is of notable significance since it is probably the boundard fault at the southern end of the central Canelo Hills block. This fault follows Western Canyon through sections 17, 18, 19, and 24. For that reason, it has been named the Western Canyon fault. This cross-fault is mapped on the basis of exposures in section 24 and extended down the canyon along a change in the alluvial cover.

Along state highway 83, the alluvial cover is predominantly volcanic debris. This changes sharply to a greater abundance of limestone rubble along the fault as shown in Figure 1. Believing that the alluvium reflects the underlying rock type, the Western Canyon fault was extended. This seems logical since the hills on the east side of highway 83 consist mainly of the welded tuff member of the Canelo Hills Volcanics.

Best exposures of the Western Canyon fault are in section 24. At this locale, it is evident that the basal member of the Canelo Hills Volcanics are positioned against the intermediate member of the same formation. The amount of displacement cannot be accurately determined since the area is affected by other faulting. However, east of the Western Canyon fault, the upper beds of the basal Canelo Hills Volcanics must be offset towards the north at least one mile. This would require a vertical displacement of at least 2,600 feet. Strike-slip movement is unknown, if present.

EXOTIC BLOCKS

Large exotic blocks of Upper Paleozoic limestone, enclosed or underlain by the basal and intermediate members of the Canelo Hills Volcanics Group, are common in the area of Canelo Pass. Others are known in the area northeast of Canelo Pass where only reconnaissance work was done. Figure 1 shows the distribution and size of the exotic blocks.

The exotic blocks appear to have been emplaced by gravity slumping or landsliding. Such a hypothesis would adequately explain the anamalous features associated with the blocks, i.e., the fact that they are found at many stratigraphic levels in the thick Canelo Hills Volcanics Group; the apparent lack of order of blocks of various-aged rocks; and the attachment of Paleozoic limestone and Triassic-Jurassic sandstone to form a single exotic block overlying Triassic-Jurassic rhyolite.

Other interpretations exist; it is possible that the blocks represent the erosional remnants of Post-Paleozoic thrust plates. This theory would require renewed thrusting to have occurred following the erosion of previous thrust plates and the inclusion of the erosional remnants in the accumulating Canelo Hills Volcanics deposits. This is a rather complicated process, especially for an area completely lacking in other compressional features. Another theory proposed for the emplacement of the exotic blocks, (Simons, Raup, and Hayes, 1966), combines sporatic landsliding with rafting of some blocks by lava flows. The second part of this theory has no precedent known to this writer. In addition, it would seem to require some contact metamorphism of the limestone blocks. Metamorphic changes were not evident in the central Canelo Hills.

REGIONAL IMPLICATIONS OF THE EXOTIC BLOCKS

Two earlier works concerning the geology of the Canelo Hills have described thrust faults. Feth (1947), working in the area of Mount Hughes, mapped Permian limestones thrust to the southwest onto Cretaceous (?) redbeds and Tertiary volcanics. The present writer briefly visited the area and believes that the redbeds and volcanic rocks are the northern equivalents of the lower two members of the Canelo Hills Volcanics. If this is so, exotic blocks may be present. Fenster and klippen, as described by Feth, could be due to the exposure by erosion of exotic blocks enclosed in the Canelo Hills Volcanics. One would expect landsliding to also produce brecciation of the blocks as Feth describes.

Further, an exposure of exotic blocks along a line could easily be mistaken for outcrops along a thrust fault. This is especially true in areas of poor exposures as in the Canelo Hills. Simons, Raup, and Hayes, 1966, have published a map showing a front of exotic blocks along the contact of the Concha Limestone with the Canelo Hills Volcanics a few miles southeast of Mt. Hughes.

The writer has observed exotic blocks in the SE 1/4 of section 33, T20S, R16E, and the NE 1/4 of section 3, T21S, R16E at the northern end of the Canelo Hills. These appear to crop out along a normal fault that dips 60° towards the southwest. This fault positions the basal member of the Canelo Hills Volcanics against Paleozoic Limestone.

In an area less than two miles north of the immediate area of study, Cetinay, 1967, describes a northeast directed thrust of Paleozoic rocks onto "Upper Cretaceous" rocks. The writer has visited the area and found the basal unit of the Canelo Hills Volcanics to exist in fault contact with both Paleozoic rocks to the west and the Cretaceous Bisbee Group on the east.

Apparently Centinay believes the large blocks of limestone present in this area of Mesozoic sediments are klippen cut off from other Paleozoic sediments by erosion. An alternative hypothesis to the thrust described by Cetinay is that large gravity-transported blocks of Paleozoic limestone are interbedded with the basal Canelo Hills Volcanics. These blocks are today exposed by erosion along a normal fault.

If the exotic block hypothesis presented in the above paragraphs can be positively proven, previous ideas on structural relations may warrant reappraisal elsewhere. This is especially true in areas near the Canelo Hills where Paleozoic rocks have been interpreted as thrust onto "Cretaceous (?)" rocks. The existence of exotic blocks interbedded in younger sediments should not be considered unique to the Canelo Hills, however. Such features have been recognized in distant places such as Syria, Iran, and Venezuela (North, 1964). Closer at hand, they are also described in the Patagonia Mountains and Santa Rita Mountains (Simons, Raup, and Hayes, 1966).

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