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Rio Grande Gorge highway corridor study, Rinconada to Pilar

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COMPLETION REPORT

RIO GRANDE GORGE HIGHWAY CORRIDOR STUDY, RINCONADA TO PILAR

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PURPOSE AND SCOPE

This report is the result of a reconnaissance engineering geologic study, commissioned by the New Mexico State Highway and Transportation Department (NMSHTD), to evaluate the geologic feasibility of a highway route along the northwestern side of the Rio Grande gorge between the towns of Rinconada and Pilar. Such a route would require the construction of two major bridges over the Rio Grande and the underlying Embudo fault, and would pass through approximately six miles of landslide terrain as well as potentially hydrocompactive and liquefiable deposits. The objectives of this study were to :

1) Summarize existing information about the geology of the proposed route, including regional earthquake hazards.

2) Produce an engineering geologic map of a possible highway corridor delineated by NMSHTD, based primarily on surficial geology and augmented by a limited amount of shallow soil sampling and laboratory testing.

3) Render an opinion on the overall geologic feasibility of a highway route along the northwestern side of the Rio Grande gorge, and compare the advantages and disadvantages of the northwestern route to those of the existing southeastern route.

4) Issue a set of recommendations for further geologic and geotechnical work that will be necessary should the northwestern option be pursued.

Project personnel were Dr. William C. Haneberg, an engineering geologist with the New Mexico Bureau of Mines and Mineral Resources (NMBMMR); Dr. Paul W. Bauer, a field geologist with NMBMMR; and Dr. William X. Chávez, Jr., an associate professor of geological engineering at the New Mexico Institute of Mining and Technology (NMIMT). Ms. Lisa Buto, a graduate student in geological engineering at NMIMT, assisted with sample analysis and map preparation.

The proposed highway route is covered by 1:24,000 geologic maps (USGS Trampas and Carson 7.5' quadrangles) currently in preparation by Bauer, as well as a regional (1:125,000) geologic map by Kelley (1978), and an NMSHTD aggregate resources map. Although all of these maps show Quaternary landslide deposits along the proposed route. Regional landslide inventory maps based on air photo interpretation with limited field checking (Guzetti and Brabb, 1987) also show Toreva block slide deposits along the proposed route. None of these maps, however, distinguish among active, potentially active, and inactive landslides.

PROBLEMS WITH THE CURRENT ROUTE

The current route of NM 68 between Rinconada and Pilar is plagued by a host of actual and potential geologic hazards. The height of the Pilar cliffs, combined with fracturing along the Embudo fault zone, promote damaging and, in one instance, fatal rockfalls. Steep, debris clogged drainage basins along the Picuris Mountain front also provide source areas for potentially dangerous debris flows during rainstorms. During the winter months, this portion of NM 68 is also icy in many places.

On September ~~5~~ 12, 1989, five people were killed and fourteen injured when a large basalt boulder, loosened during a rainstorm, struck a commercial bus. On the evening of July 25, 1991, following several days of hard rain, 11 debris flows and numerous rockslides and/or rockfalls cascaded onto NM 68 along the base of the Pilar cliffs, trapping 20 cars and closing the highway for 19 hours. Approximately 3000 cu yd of fill were required to repair the damage, at a cost of about $75,000. A $45 \times 15 \times 15$ ft crater was formed when a 300 ton boulder travelled from an outcrop near the top of the cliffs and struck the roadway. After impact, the boulder came to rest near water level on the opposite side of the Rio Grande, where it remains today. Preliminary calculations suggest that the boulder had a velocity of about 47 mi/hr and a kinetic energy of 30,000 ft·tons at impact, which is several hundred times the capacity of commercially available rockfall protection nets (Haneberg and Bauer, 1992). The largest debris flow on the highway was about 100 ft wide and 8 ft thick. Deposits along the river suggest that another debris flow, which was channeled through a culvert, temporarily dammed the Rio Grande.

In addition to hazards posed by near-surface geologic processes, there is a poorly understood seismic hazard along the Rio Grande rift. Existing information on seismic hazards in northern New Mexico is summarized in a subsequent section. With regard to the present route, it is possible that a moderate to large earthquake in the region would destabilize steep talus slopes and isolated large boulders above the highway. If a moderate to large earthquake coincided with a period of abnormally high rainfall, it is possible that landslides and debris flows would be generated as well.

REGIONAL GEOLOGY

Southwest of Pilar, the Rio Grande gorge trends northeast-southwest along the Embudo fault, a major Neogene structure that separates Tertiary deposits of the Taos Plateau from Proterozoic rocks of the Picuris Range (Fig. 1). To the south, the Embudo fault merges with the Pajarito fault (Los Alamos fault of Manley, 1984); to the north, the Embudo fault merges with the range-bounding Sangre de Cristo fault zone (*e.g.*, Personius and Machette, 1984; Menges, 1990). Vertical movement along the fault, combined with erosionally resistant upthrown Proterozoic rocks, led to the development of a 3 mi long, 1000 ft high bluff of highly fractured crystalline rocks, known as the Pilar cliffs. The Picuris Range is a fault-bounded, wedge-shaped uplift that projects westward from the southern Sangre de Cristo Mountains, forming part of a constriction that separates the Española and San Luis structural basins in the northern Rio Grande Rift. The present, deeply eroded Picuris block rose rapidly about 3-5 Ma, and has remained high since that time (Manley, 1984).

The Embudo fault, which passes directly beneath the proposed highway corridor, is a segment of a much larger, northeast-southwest trending structure, the Jemez lineament, that has apparently been a zone of crustal weakness since late Precambrian time. Muehlberger (1979) has estimated minimum structural relief of 10,000 ft across the Embudo fault. The rhomb-shaped Picuris crustal block, bounded by the Embudo, Pircuris-Pecos, Tijeras-Cañoncito, and Pajarito fault systems, has rotated counterclockwise through time (Muehlberger, 1979; Aldrich, 1986; Aldrich and Dethier, 1990). The pivot point is located near Pilar, resulting in a complicated variety of fault motions along the north flank of the Picuris Mountains. These include reverse faulting between Pilar and Taos, down-to-the-north normal faulting southwest of Pilar, and left-lateral strike slip along the southwestern trace of the fault zone (Muehlberger, 1979; Aldrich, 1986).

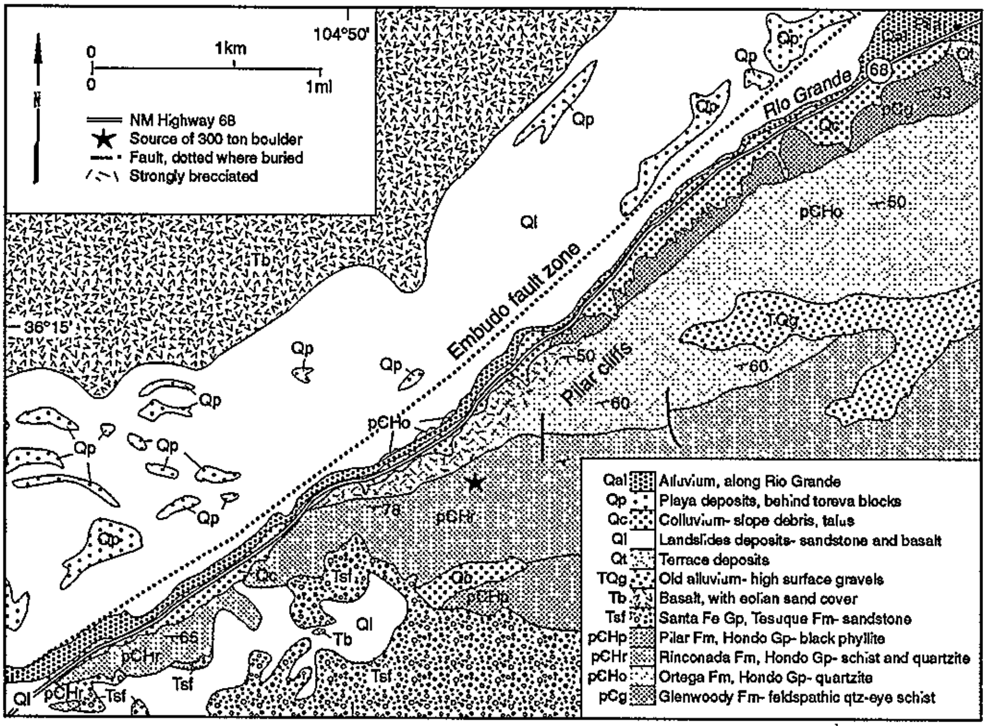

Figure 1.– Generalized geology of the Rio Grande gorge between Rinconada and Pilar, taken from 1:24,000 geologic quadrangle maps by P. Bauer, currently in preparation.

The oldest Precambrian unit in the Pilar cliffs is the Glenwoody Formation, consisting of approximately 600 ft of homogeneous, feldspathic metavolcanic-metavolcaniclastic quartz-eye schist that accumulated at 1700 Ma (Bauer and Williams, 1989). The Glenwoody Formation is overlain by the 6600 ft thick Hondo Group, a metasedimentary section of cliff-forming quartzites, pelitic schists, and phyllites. All units are polydeformed, metamorphosed to amphibolite facies, and moderately south-dipping. In addition to exposures in the Pilar cliffs along the southeastern side of the Rio Grande, there are limited exposures of Hondo Group schists and quarzites along the northwestern side of the river between the Glenwoody bridge and Rinconada. The July 1991 rockslide boulder came from an outcrop of the lowermost schist unit of the Hondo Group. North of the Picuris block, basement rocks are bounded by Tertiary sedimentary and volcanic rocks deposited in Rio Grande rift basins. The Tesuque Fm. (Miocene to Pliocene) of the Santa Fe Group is a sequence of poorly sorted, weakly consolidated sand, silt, and gravel beds that range in thickness from 500 to 3500 ft. In the study area, Tesuque Fm. sands and gravels are found only at the top of the Pilar cliffs. These deposits are capped by tholeiitic basalts of the Pliocene Servilleta Formation. Between Pilar and Embudo, where erosion by the Rio Grande has over-steepened slopes underlain by Tertiary rocks, landslide debris consisting primarily of basin fill sands and gravels, as well as basalt boulders, covers much of the river valley. The September 1988 rockfall boulder was derived from such a deposit along the southeastern side of the river.

Between Rinconada and Pilar, the northwestern side of the Rio Grande gorge is cut into Cenozoic basin-fill deposits of the Chamita Fm. (Miocene to Pliocene) of the Santa Fe Group. The Chamita Fm. ranges from a lower section of buff-colored, moderate- to poorly-sorted sands with clasts of intermediate volcanic rock, quartzite, and other metamorphic rocks; to a middle section with fewer volcanic clasts and more metamorphic clasts; and to an upper section devoid of volcanic clasts. Sedimentary structures are scarce. Unlike the stratigraphically lower Tesuque Fm., the Chamita Fm. is not known to contain localized silty and/or clayey layers that could contribute to slope stability problems if saturated. Overall, the unit coarsens upwards and is overlain by Servilleta Fm. basalt flows. In response to downcutting by the Rio Grande, the Chamita Fm. has failed as a complicated mass of large rotational Toreva block slides along the gorge. The engineering geologic implications of the Toreva blocks is discussed in detail further on in this report.

REGIONAL SEISMICITY

The historical seismicity of New Mexico, inferred from instrumental observations during the past 30 years, generally ranges from low to moderate. Sanford *et al.* (1991) list only six earthquakes of magnitude 3.5 or greater in New Mexico between January 1962 and September 1986. Recent seismic activity has included a swarm of 34 earthquakes of magnitude 2.0 to 4.7, with epicenters between Belen and Socorro, between late November 1989 and early April 1991 (A.R. Sanford, personal communication, 1991), as well a a magnitude 5 earthquake in southeastern New Mexico in January 1992 (Sanford *et al.*, 1992). Based upon extrapolation of instrumental data collected between 1962 and 1975, Sanford *et al.* (1981) predict one earthquake of magnitude 4.8 every 50 years and one earthquake of magnitude 5.1 every 100 years. Similar estimates suggest an earthquake of between magnitudes 4.5 and 5.0 with an epicenter within 70 km of Los Alamos once every 100 years (House and Cash, 1988).

In north-central New Mexico, reservoir-induced seismicity has been documented near El Vado and Heron reservoirs (Cash and Wolff, 1984; El-Hussain and Carpenter, 1990) between 1976 and 1984. Maximum magnitude of the induced earthquakes was 2.7, with a sharp drop in the frequency of higher-magnitude earthquakes. Cash and Wolff (1984) also ascribed low-magnitude seismicity between Los Alamos and Taos during the period 1973-1983 to the Velarde fault. Their seismogenic Velarde fault, however, appears to be a composite of the Arroyo de la Presta, Velarde, and Embudo faults of Manley (1984).

Nationwide 1:7,500,000 probabilistic earthquake acceleration and velocity maps by Algermissen *et al.*

(1990) show horizontal accelerations (in rock) of 0.025 to 0.050 *g* and 0.075 to 0.100 *g* with a 90% probability of not being exceeded in 50 and 250 years, respectively. Likewise, the same set of maps shows horizontal velocity (in rock) of 2.5 to 5.0 and and 5.0 to 7.5 cm/sec with a 90% probability of not being exceeded in 50 and 250 years, respectively. Horizontal acceleration and velocity in saturated unconsolidated deposits, for example flood plain alluvium and wet meadows, may be several times greater than that in underlying rock (*e.g.*, Reiter, 1990, p. 147-163). A consultant's report, cited in House and Cash (1988), recommended that a maximum horizontal acceleration of 0.33 *g* be used for facilities design at Los Alamos National Laboratory. Although it is wholly inappropriate to use these generalized values as a basis for site-specific engineering design, they do provide a useful first-order assessment of regional seismic hazards.

Recent paleoseismic studies along the northern Rio Grande rift have yielded results that seem to suggest a level of seismicity higher than that extrapolated from historical records. Menges (1990), in particular, found evidence of Pleistocene and Holocene earthquakes with characteristic magnitudes of 5.8 to 7.1, for single- and multiple-segment ruptures, and recurrence intervals on the order of 10^4 years along the Sangre de Cristo fault zone north of Taos. Paleoseismic studies of the Pajarito fault near Los Alamos National Laboratory (Gardner and House, 1987), which yielded characteristic magnitudes ranging from 6.5 to 7.8, with recurrence intervals for magnitude 6 earthquakes ranging from 100 to 10,000 years. In several roadcuts along the NM 68 north of the proposed highway corridor, the Embudo fault is marked by 20 to 50 ft high fault scarps that displace early to middle Pleistocene deposits, with the last movement inferred to have occurred in the late Pleistocene (Personius and Machette, 1984). The magnitude-frequency discrepancy between instrumental observations and paleoseismic inferences throughout New Mexico has also been reported elsewhere, and may indicate either that 1) current instrumental observations are being made during a seismically quiescent time, or 2) that the characteristic earthquake concept used to estimate paleoseismic magnitudes is inappropriate (Reiter, 1990, p. 206-209).

ENGINEERING GEOLOGIC MAP OF THE PROPOSED CORRIDOR

Because the proposed route is covered by quadrangle-scale geologic maps currently in preparation, field work for this project consisted of walking the route to look for evidence of stability and/or instability and to classify surficial deposits based upon their engineering properties.

Field work was conducted over a period of three days in May 1992. Field observations were recorded on 1:13,800 (1":1150') photocopy base maps provided by NMSHTD, which had been enlarged from 1:24,000 (1":2000') USGS topographic maps of the Carson and Trampas quadrangles. Although the contract authorizing this work specified mapping of a corridor 500 ft on either side of the proposed highway alignment, the actual width of the mapped corridor was increased to at least 1000 ft on either side of the alignment. This was done in order to better represent surficial map units along the route, which typically extend several hundreds of feet from the proposed alignment. Aerial photographs, flown for this project and provided by NMSHTD, were also carried in the field. Some shallow samples were collected from fine grained slope wash/playa deposits along the route for further laboratory study. In the office, the aerial photos were examined stereographically, and geologic information recorded on the topographic base was reconciled with the aerial photos using a Bausch & Lomb zoom transfer scope.

Engineering Geologic Map

The Genesis-Lithology-Qualifier (GLQ) system of engineering geologic map units (Keaton, 1984) is especially well-suited for the present project because it conveys information regarding the texture, geomorphology, and the depositional environment of surficial deposits (engineering soils) while at the same time eliminating superfluous geologic information not necessary for engineering design and construction. GLQ map symbols for unconsolidated deposits consist of an upper-case genetic descriptor, one or more lower-case lithologic descriptors, and, in parentheses, an optional lower-case geomorphic or genetic qualifier. Rock types are denoted by a series of double letter, upper-case symbols. The only two rock type symbols used in this report are QT (quartzite) and SC (schist). Special properties that may have an impact on engineering design and/or construction are denoted by a lower case prefix; in this report, for example, the prefix "h" denotes the possibility of hydrocompactive or collapsible soils. Table 1 lists the genetic and qualifier symbols and Table 2 the GLQ lithologic symbols used in this report.

Table 1.– GLQ genetic and qualifier symbols used in this report (selected from Keaton, 1984).

Genetic Symbol		*Optional Qualifier Symbol*	
S	slide deposit	(tr)	translational slide
		(ro)	rotational slide
A	alluvial deposit	(fp)	flood plain alluvium
		(te)	terrace alluvium
C	colluvial deposit	(sw)	slope wash deposit
		(ta)	talus

Table 2.– GLQ lithologic symbols for unconsolidated deposits (selected from Keaton, 1984).

o	organic
c	clay
m	silt
s	sand
k	cobble
b	boulder

Application of the GLQ system is best illustrated by way of example. A sandy to bouldery stream terrace deposit would be denoted by the GLQ symbol As-b(te), and a bouldery talus slope would be indicated by the GLQ symbol Cb(ta). If something is known about the stratigraphy of the deposits being mapped, superposition can be indicated by stacking GLQ symbols. A clayey translational landslide deposit underlain by sand and gravel flood plain alluvium, for example, would be denoted by:

$$\frac{\text{Sc(tr)}}{\text{Asg(fp)}}$$

Based upon a generalization of field observations during the study period and previous visits, deposits encountered along the proposed route were divided into the GLQ map units described below.

Rotational Slide Blocks (Toreva Blocks), Ss-b(ro).– Landslide blocks consisting of internally stratified basin fill sands and gravels of the Cenozoic Chamita Fm. and capped by erosionally resistant basalt flows of the Servilleta Fm. Regionally, these rotational slides are known as Toreva blocks (Reiche, 1937), after the type location of Toreva, Arizona. Silt and/or clay are only minor constituents of the Chamita Fm. In many cases, there is little disruption of internal stratification and, due to their large size, the blocks can be easily misidentified as undisturbed outcrops of Chamita Fm. Moderately well-developed, 3 to 6 ft thick calcic soil horizons (Stage II and/or III of Gile *et al.*, 1966) are present in some stream cuts; however, these have not yet reached the petrocalcic stage and should not present problems during construction.

Debris Slide Complexes, Soc-b(tr).– Slope failures that are mapped as debris slide complexes in this report consist of sand, gravel, and basaltic boulders locally mobilized from Toreva block [Ss-b(ro)] deposits. The debris slide complexes can be distinguished from Toreva block deposits by their lack internal stratification and lobate, almost flow-like, morphology. Based upon subsurface projection of slope geometry, the thickness of Soc-b(tr) deposits is estimated to be on the order of 5 to 10% of the slide length, and the mode of movement of these thin slides is inferred to be predominantly translational. Surfaces of the debris slide complexes consist of both dry sandy to bouldery ridges and wet meadows or *cienegas*. The ridges and meadows are too small to be shown individually on the engineering geologic map The *cienegas* are characterized by a dark gray to black, plastic, sandy organic clay (commonly with a sulfurous odor) near the ground surface; grass and deciduous vegetation, as opposed to piñon-juniper and succulent vegetation in drier areas; and scarps ranging from incipient cracks to well-developed rupture surfaces up to several feet high.

Landslide Deposits of Uncertain Origin, Ss-b.– Landslide deposits consisting of poorly sorted sands, gravels, and basaltic boulders, restricted to the southeastern side of the Rio Grande near Rinconada. Except for an absence of *cienegas*, these deposits are texturally and lithologically similar to the debris slide complexes [Soc-b(tr)] described above.

Slope Wash and/or Playa Deposits, hCms(sw).– Fine-grained, orange to buff silt and fine sand accumulated in topographic depressions behind Toreva block dip slopes. In some cases, slope wash/playa deposits surround partially buried islands of Toreva block material. These deposits were unsaturated to 4 ft in one hand auger hole and to 8 ft in another, with no visible reduced organic matter or other evidence of long-term saturation. On the ground and on aerial photos, these deposits are identified on the basis of their flatness relative to surrounding terrain, fine-grained soils, and dominant sage vegetation. The geologic youth, depositional environment, and texture of these deposits suggests that they may be hydrocompactive.

Flood Plain Alluvium As-b(fp).– Modern alluvial deposits restricted to the present-day course of the Rio Grande and young abandoned channels, ranging from sand to boulders. Likely to be saturated to the ground surface or nearly so.

Stream Terrace Deposits As-b(te).– Fragmented, older alluvial deposits cut by present-day Rio Grande and related channels. Stratigraphic exposures are poor; thus stream terraces were mapped solely on the basis of geomorphology. Their slightly higher elevation implies that water tables will not be as high as in flood plain alluvium.

Talus Slopes Cb(ta).– Many Toreva block dip slopes northwest of the Rio Grande are covered with a relatively intact layer of polygonally jointed Servilleta Fm. basalt with little evidence of downslope movement. In other places, previously intact basalt caps have collapsed due to erosion of underlying sands and gravels, producing jumbles with a boulder ranging in size from a cubic foot to 20 or 30 cubic yards. Because these basalt slopes have been formed in place after Toreva block movement, both types are mapped as colluvial lithogeomorphic units within the Toreva block terrain. Although much of the Toreva block terrain is littered with basalt boulders to one degree or another, only the most heavily covered slopes were classified as separate map units. Southeast of the river, portions of slopes above the present highway are covered with quartzite and schist boulders.

Quartzite, QT.– Gray to grayish-white, medium- to coarse-grained quartzite of the Precambrian Ortega Fm. of the Hondo Group. Generally massive and erosionally resistant, but can be highly fractured in outcrops near the Embudo fault zone. Grades downward into Glenwoody Fm. schist (SC).

Schist, SC.– Feldspathic quartz-muscovite schist of the Glenwoody Fm., exposed in cliffs southwest of Pilar. White, light gray, pink, or green. Contact with the overlying Ortega Fm. (QT) is believed to be the remnant of a ductile shear zone, and lineations plunge to the south.

GEOLOGIC HAZARDS MAP OF THE PROPOSED CORRIDOR

Stable and Unstable Ground (ST and UST)

In addition to identifying landslide deposits, it is important to establish the relative stability or instability of the deposits. Some deposits, although the products of past slope instability, may have remained stable for hundreds or thousands of years. As long as adequate engineering precautions are taken, such deposits can be considered stable under present conditions and suitable for construction. Other landslide deposits may be actively moving, and unsuitable for construction. Several criteria that can be used to distinguish between active and inactive landslide complexes are listed in Table 3.

Debris slide *cienegas* along the proposed highway corridor are most likely the result of upward seepage, and the existence of dark gray to black soils with a sulfurous odor implies that the meadows are in a state of chemical reduction (as opposed to oxidation) and have been persistently saturated. The combination of upward-directed seepage forces and extremely shallow water tables greatly increases the likelihood of liquefaction and/or landsliding during an earthquake. The combination of persistent but localized zones of saturation in low-lying areas portions of the debris slide complexes, fresh cracks and scarps, and a preponderance of grasses and deciduous trees indicates that all of the debris slide complexes are currently active. Topographic map (1:24,000) patterns also show that debris slide lobes have altered the course of the Rio Grande, and it is conceivable that the river was temporarily blocked by debris slides at some time in the past. *Cienegas* along the southern portion of the route were saturated during a visit by Haneberg and NMSHTD personnel in December 1991, so the meadows have probably been saturated for at least six months. Classification of the *cienegas* as wetlands would more than likely eliminate drainage as a possible method of slope stabilization.

Table 3.– Features used to distinguish between active and inactive landslides (modified from Crozier, 1984).

Active	*Inactive*
Scarps and cracks with sharp edges	Scarps and cracks with rounded edges
Cracks lack secondary filling	Cracks filled with secondary deposits
Freshly striations on shear planes	Weathered striations on shear planes
Fresh crack surfaces	Weathered crack surfaces
Disarranged drainage; many ponds	Integrated drainage system
No pedogenic soil on rupture surfaces	Pedogenic soil developed on rupture surfaces
Fast-growing vegetation	Slow-growing vegetation
Different vegetation on slide mass	No changes in vegetation
Tilted trees with no new vertical growth	Tilted trees with new vertical growth
No new secondary tissue on tree trunks	New secondary tissue on tree trunks

Maintenance problems along a natural gas pipeline on the northwestern side of the Rio Grande gorge provide independent confirmation that the debris slide complex located at near mile 2 of the proposed route is currently active (Terryn Adams, Gas Company of New Mexico, personal communication, June 1992). According to Mr. Adams, major problems began in 1986, when the pipeline was sheared by a landslide. In order to prevent future failures, the pipeline was placed above ground on the timbers across two active debris slide complexes and anchored, in presumably more stable ground, with cables. A recent inspection by Mr. Adams and a geologic consultant revealed a 10 to 15 ft wide fissure about 100 ft above one of the pipeline crossings. Although there are no quantitative data available, Mr. Adams states that movement appears to be rapid and proportional to rainfall. The company is also concerned about the possibility of rockfall damage to the pipeline and tiebacks.

Any highway alignment crossing the crowns of these active debris slide complexes would require expensive, and not necessarily foolproof, stabilization measures such as lightweight fill, pier walls, half-bridges, and/or shear keys. Unless care is taken to transfer the entire weight of the highway to underlying stable Toreva block deposits, a highway across debris slide crowns would promote instability and accelerate movement of these currently active slopes. Without detailed geotechnical site investigations, however, the remedial measures that would be necessary to build a highway across the active debris slides are only speculative. If slope stability were the only concern, then it would be desirable to drain the debris slide *cienegas* as well; however, adverse environmental impacts will probably render drainage an unacceptable option. Therefore, both the Engineering Geologic Map and the Geologic Hazards Map contain an alternative, geologically preferable, route that completely bypasses the active debris slide complexes.

In contrast to the debris slide complexes, the Toreva block deposits [Ssb(ro)] mapped during this study appear to be stable under present conditions. Drainage patterns are well-integrated, and no fresh scarps or cracks were found. Arcuate head scarps, although discernible on 1:24,000 topographic maps, have in many cases been buried by slope wash deposits and covered with an open piñon-juniper forest. The existence of basalt boulder jumbles were supporting basin fill sands and gravels have been eroded away likewise suggests that a great deal of time has passed since sliding occurred. This evidence for long-term stability is consistent with the conclusions of researchers who attribute large-scale slope Toreva block movement in northern Arizona (Rieche, 1937) and northwestern New Mexico (Watson and Wright, 1963) as an effect of a colder and wetter Pleistocene climate.

It is possible that long-term precipitation changes may have a destabilizing effect on slopes, especially some of the inactive Toreva blocks along the Rio Grande gorge. A Toreva block slide occurred along an outlier of the High Plains escarpment, known as Twin Mesa, in DeBaca County during early September 1991. Precipitation during the previous year had been well above average, and approximately 50 cm of rain had fallen in nearby Ft. Sumner during late summer 1991 (Robert Russ, DeBaca County Disaster Preparedness Coordinator, personal communication, 1991). During 1983 and 1984, the reversal of a 93 year long precipitation deficit resulted in severe landslide and debris flow problems throughout the Wasatch Mountains of Utah (Fleming and Schuster, 1983). There are not enough data available to quantitatively predict the types and magnitudes of weather changes necessary for reactivation of Toreva block slides in northern New Mexico. It is possible, however, to examine the meteorological context in which qualitative interpretations of slope stability and instability are made. In this way, observations of stable slopes made during abnormally dry periods might be given less weight than observations of stable slopes made during abnormally wet times. An attempt was made to obtain relevant precipitation records from the New Mexico Department of Agriculture; unfortunately, the position of State Climatologist was abolished in 1985 and meteorological records have been lost (Larry Dominguez, New Mexico Department of Agriculture, personal communication, 1992). Precipitation data could not be obtained from the National Climatic Data Center in a timely manner, so Rio Grande stream flow data available at the New Mexico Tech library were used as a proxy. Although the stream flow data contain contributions from many drainages throughout the northern Rio Grande basin, they should provide a generalized picture of the wetness or dryness of northern New Mexico for any given year. The stream flow data, plotted in Figure 2, illustrate apparently random fluctuations about a logarithmic mean of 888 cfs between 1889 and 1990, with no evidence of a long-term water deficit or surplus. Therefore, interpretations of long-term Toreva block stability appear not to be aberrations resulting from observations made in unusually dry times.

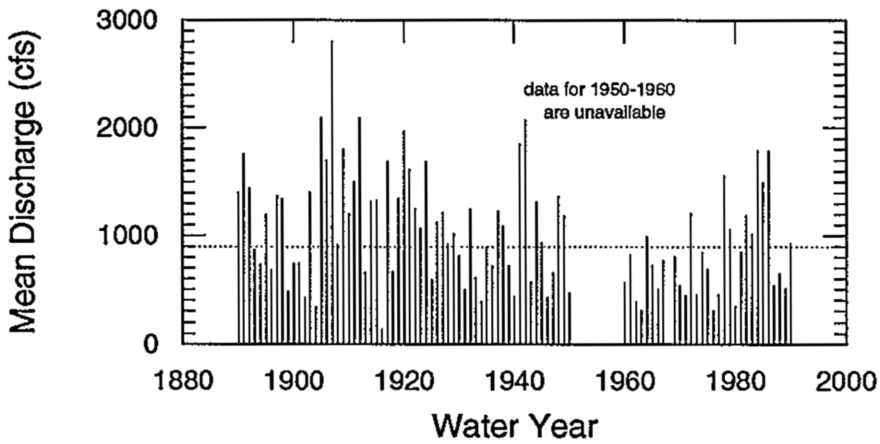

Figure 2.– Mean discharge, Rio Grande at Embudo, for water years 1889-1990. Data compiled from U.S. Geological Survey Water Supply Papers shelved at the New Mexico Tech library.

There is also some potential for rockfalls or rockslides along parts of the proposed route, especially near the feet of slopes covered with basalt boulders. Because boulders are so abundant along the proposed highway corridor, it was not possible to delineate meaningful rockfall hazard zones as part of this study. Slopes along the northwestern side of the gorge are much less steep than those along the southeastern side, and there is much less relief along the southwestern side as well. Because the kinetic energy of a rolling or sliding boulder is a function of both slope and relief (Haneberg and Bauer, 1992), rockfalls along the proposed route will probably be less severe than those affecting the current route. It is also likely that the potential for rockfalls at any given location along the proposed route will be greatly affected by design and construction, especially where hillslopes are steepened by road cuts. Therefore, the potential for rockfalls should be assessed during and after construction, when the effects of road cuts can be evaluated, using standardized inventory methods (*e.g.*, Stover, 1992; Pierson *et al.*, 1990).

The secondary effects of a large earthquake near the proposed route may include a widespread increase in slope instability, including landslides, debris flows, and rockfalls. At present, there are not enough data available to quantitatively evaluate effects of a large earthquake on slope stability. It is likely, however, that currently active debris slides would be more likely to be affected than Toreva blocks. The potential for earthquake-induced rockfalls appears to be much greater along the present highway route, above which lie steep talus slopes. There is also a possibility that a combination of excessive precipitation and a large earthquake might combine to destabilize some Toreva blocks; over the design life of the proposed highway, however, this coincidence is probably unlikely.

Potentially Hydrocompactive Deposits (HY)

Sage flats underlain by slope wash/playa [hCms(sw)] deposits along the proposed highway corridor would provide a flat to gently rolling grade. The sedimentological and geotechnical characteristics of these geologically young deposits, however, suggest that there is a potential for hydrocompaction (collapse) if the deposits are wetted.

Hydrocompactive soils lose a significant amount of volume through reduction of porosity when wetted, and have damaged roads and structures in several parts of northern New Mexico. Research near El Llano, east of Española, by NMBM&MR (Johnpeer *et al.*, 1985a,b; Shaw and Johnpeer, 1985a,b) and along I-25 near Algodones by the New Mexico State Highway Department (Lovelace *et al.*, 1982) has produced a large body of information concerning the identification and mitigation of hydrocompactive deposits and associated engineering problems. Reimers (1986) conducted a geotechnical study of hydrocompactive deposits at El Llano, including stepwise multiple regression and discriminant function analyses, in an attempt to delineate index properties that might be used to identify potentially hydrocompactive soils.

The results of NMBM&MR research, cited above, show that hydrocompactive deposits at El Llano are the products of frequent mud and/or debris flows during the past several thousand years. El Llano hydrocompactive deposits are typically composed of poorly- to well-graded sands, silty sands, and/or clayey sands (*e.g.*, Unified Soil Classification System SW, SP, SM, SC) that have been eroded from geologically young parent material, typically Cenozoic basin fill sands and gravels in New Mexico. Drainage areas and relief ratios of hydrocompactive landscapes tend to be small. Typical index properties for hydrocompactive soils studied at El Llano are listed in Table 4.

Table 4.– Generalized geotechnical index properties of hydrocompactive soils near El Llano, New Mexico (modified from Johnpeer *et al.*, 1985 b).

Index Property	*Typical Values*
Texture	USCS SW, SP, SM, or SC
Dry Density	75–95 pcf
Void Ratio	0.5–1.0
Moisture Content	4–10% by weight
Degree of Saturation	< 60%
Liquid Limit	0–40
Plastic Limit	0–20
Total Consolidation Upon Wetting	> 5%
Soil Grain Specific Gravity	2.50–2.65
Clay Mineralogy	smectite, illite, mixed-layer, kaolinite
Blow Count (N value)	< 18
P-wave velocity	< 1000 ft/sec

Reimers (1986) was able to account for 96% of the variability of the collapse potential, R, of El Llano soil samples using a multiple logarithmic regression model that took into account the liquid limit, plasticity index, pre-collapse density, and the weight percent of material passing a #200 sieve. The collapse ratio, is the liquid limit divided the gravimetric moisture content at saturation. If $R > 1$, then hydrocompaction upon wetting is predicted; if $R < 1$, then hydrocompaction is not predicted. Because this regression model was developed specifically for El Llano soils, it should be applied to other areas only with caution and must never be used as the basis for engineering design.

In order to provide a first-order assessment of the hydrocompactive potential of slope wash/playa deposits [hCms(sw)] along the proposed highway corridor, disturbed samples from two shallow hand auger holes were collected and returned to the laboratory for routine geotechnical analysis. These auger holes are both located along the northeastern half of the proposed route, where an existing road provided vehicular access; however, there is no geologic reason to believe that slope wash/playa deposits along the southeastern portion should be substantially different. Test results for these two boreholes are listed in Tables 5 and 6. Boreholes 1 and 2, which were located close to borehole 3, encountered rock (probably basalt boulders) at a depth of about one foot and were abandoned.

Table 5.– Selected geotechnical index properties of slope wash/playa deposit auger samples, borehole #3 (NE/4, SE/4, SE/4, sec. 31, T24N, R11E).

Depth	*LL*	*PL*	*PI*	*w*	*% fines*	*USCS Symbol*
0.8-1.2	33.1	22.5	10.6	18.2	14.8	SC
1.2-1.5	--.-	--.-	--.-	17.9	14.9	---
1.5-1.9	40.0	20.2	19.8	17.9	13.3	SC
1.9-2.3	38.4	20.2	18.2	17.4	20.4	SC
2.3-2.5	--.-	--.-	--.-	15.7	16.1	---
2.5-2.9	36.1	20.4	15.7	13.3	11.3	SW-SC
2.9-3.2	32.5	17.2	5.3	11.7	15.5	SM-SC
3.2-3.5	--.-	--.-	--.-	10.1	20.0	---
3.5-3.9	26.8	20.0	6.8	8.8	24.0	SM-SC
3.9-4.2	27.5	20.2	7.3	8.3	23.0	SC

Depth is given in feet below ground surface.
LL is the liquid limit expressed in wt. % moisture
PL is the plastic limit expressed in wt. % moisture
PI = LL-PL is the plasticity index expressed in wt. % moisture
w is the natural moisture content in wt. %
% fines is the wt. % of material passing a #200 standard mesh (0.075 mm) sieve
USCS symbol is the Unified Soil Classification System assignment

Test results from both boreholes show the slope wash/playa deposits to consist of silty to clayey, low plasticity sands. Whereas the borehole 3 deposits are clayey sands with moisture contents ranging from 8.3 to 18.2%, the borehole 4 deposits are silty sands with moisture contents ranging from 3.6 to 7.4%. It was impossible to estimate bulk density from the disturbed samples. Although the thickness of these deposits is not known with any certainty, projection of Toreva block surface topography beneath the small catchments suggests that thickness probably does not exceed several tens of feet. With the exception of moisture content values in the upper 3 ft of borehole 3, the geologic youthfulness, depositional environment, texture, plasticity, and moisture content of the two sample sets are consistent with geotechnical characteristics of hydrocompactive soils near El Llano. Therefore, these deposits are uniformly mapped as potentially hydrocompactive throughout the study area.

Table 6.– Selected geotechnical index properties of slope wash/playa deposit auger samples, borehole #4 (SE/4, SW/4, SE/4, sec. 31, T24N, R11E).

Depth	*LL*	*PL*	*PI*	*w*	*% fines*	*USCS Symbol*
0.4-0.9	26.4	24.6	1.8	4.0	11.8	SM
0.9-1.2	19.3	18.0	1.3	3.6	18.5	SM
1.2-1.8	22.6	21.4	1.2	5.4	38.4	SM
1.8-2.3	20.9	16.3	4.6	4.9	17.3	SM-SC
2.3-2.7	--.-	--.-	-.-	6.1	21.4	---
2.7-3.1	21.8	19.8	2.0	6.3	17.3	SM
3.1-3.3	18.3	17.4	0.9	5.2	20.7	SM
3.3-3.6	17.7	16.4	1.3	5.1	15.0	SM
3.6-3.8	19.0	18.0	1.0	5.3	11.2	SP-SM
3.8-4.2	17.1	15.8	1.3	5.2	31.7	SM
4.2-4.5	18.7	14.3	4.4	5.2	28.8	SM-SC
4.5-4.9	20.2	12.3	7.9	5.8	18.0	SC
4.9-5.2	16.7	15.6	1.1	5.3	16.8	SM
5.2-5.7	--.-	--.-	-.-	5.0	22.1	---
5.7-6.1	25.5	19.4	6.1	5.2	27.0	SM-SC
6.1-6.4	17.3	17.0	0.3	5.9	26.4	SM
6.4-6.9	19.9	16.9	3.0	6.3	28.7	SM
6.9-7.2	16.4	15.9	0.5	7.4	12.0	SM
7.2-7.6	21.8	18.7	3.1	6.8	12.4	SM
7.6-8.1	16.8	15.3	1.5	5.2	14.0	SM

Depth is given in feet below ground surface.
LL is the liquid limit expressed in wt. % moisture
PL is the plastic limit expressed in wt. % moisture
PI = LL-PL is the plasticity index expressed in wt. % moisture
w is the natural moisture content in wt. %
% fines is the wt. % of material passing a #200 standard mesh (0.075 mm) sieve
USCS symbol is the Unified Soil Classification System assignment

Potentially Liquefiable Deposits (LQ)

Alluvial deposits near river level are mapped as potentially liquefiable in this report, due primarily to an inferred shallow water table. If saturated sand layers are present within the flood plain and stream terrace alluvium, liquefaction and failure of overlying unsaturated deposits may occur during a moderate to large earthquake. There may be some potentially liquefiable alluvium buried beneath landslide debris near river level; however, the extent of buried and potentially liquefiable deposits could not be delineated on the basis of surficial geology, and no such units are shown on either the engineering geologic map or the geologic hazards map. The possible existence of liquefiable alluvium buried beneath landslide debris will be an important issue in bridge abutment design.

It is possible that presently active debris slide complexes would be liquefied during a large earthquake, and transformed from slow-moving debris slides into rapidly moving debris flows. These areas, however, are shown simply as unstable slopes (UST) on the geologic hazards map. It is possible, albeit highly speculative, that the flow-like morphology of the debris slide complexes, which differs substantially from that of the Toreva block parent material, is the result of paleo-liquefaction. Finally, it is likely that some potentially liquefiable alluvium is buried beneath landslide debris near river level.

SUMMARY AND RECOMMENDATIONS

Feasibility of the Proposed Route

Although the proposed realignment of NM 68 along the northwestern side of the Rio Grande gorge between Rinconada and Pilar is far from ideal, it is feasible from a geologic point of view. The proposed highway alignment twice crosses a major fault zone with some evidence of modern-day seismicity, and traverses some six miles of landslide terrain punctuated by potentially hydrocompactive slope wash/playa deposits. As long as these hazards are recognized, however, it should be possible to design and build a safe, albeit expensive, highway along the northwestern side of the gorge. The primary advantage a highway along the northwestern side of the gorge will be an almost complete elimination of the rockfall and debris flow hazards common along the much steeper southeastern side of the gorge. Unconsolidated deposits will allow much greater latitude in the design of cuts and fills, allowing for open curves, gentle grades, wide shoulders, and enhanced visibility. The proposed route will be well above river level along most of its course, improving aesthetics for rafters and fisherman. In addition, a higher alignment along the northwestern side of the gorge will be in the sun for much of the day, reducing winter icing problems.

Consequences of a No-Action Alternative

The impact of a highway along the proposed route must evaluated against the consequences of maintaining the current route. If properly designed and constructed, a highway along the proposed route should not promote slope instability; if anything, a properly engineered highway should increase the stability of the slopes upon which it is built. Likewise, as long as care is taken, it should be possible to build a highway that has only a minimal impact on *cienega* wetlands. The current route, in contrast, will continue to be plagued by periodic rockfalls and debris flows, as well as icy driving conditions during the winter. Although there is some chance of slope instability and hydrocompaction along most of the proposed highway corridor, these relatively slow processes are more easily dealt with than the fast-moving debris flows and rockfalls that occur along the current route.

A moderate to large earthquake would probably trigger many rockfalls along the current route, as well as debris flows if shaking were to occur during a wet period. There might be some seismically-induced landsliding along the proposed northwestern route, and, if a large earthquake were to occur along the Embudo fault *per se*, ground rupture and displacement could severely damage bridges or other engineering structures built across the fault zone. Liquefaction of saturated alluvium may cause sloughing of unconsolidated deposits along the river, perhaps damaging the current roadway. In general, however, it is possible to design and construct a highway to withstand shaking associated with a moderate earthquake.

It is also possible that an extended period of above average precipitation will increase debris slide activity, and perhaps even reactivate dormant Toreva blocks, along the northwestern side of the Rio Grande. Rapidly moving debris slide complexes could temporarily dam the Rio Grande, which is only a few tens of feet wide in many places between Rinconada and Pilar. At present, it is not possible to calculate the magnitude and duration of precipitation changes necessary to promote widespread slope instability. It is important to realize, however, that a properly engineered and constructed highway should have little or no impact on slope instability triggered by long-term weather changes. As above, a landslide moving several feet per day poses much less of a hazard to life and limb than a boulder tumbling several feet per second.

Recommendations

Based upon a review of regional geology and seismicity, reconnaissance-level engineering geologic mapping, and limited soil testing, the following recommendations are offered:

1) The economic and engineering feasibility of a new highway route along the northwestern side of the Rio Grande gorge, as described in this report, should continue to be investigated by NMSHTD. The proposed realignment has many safety advantages over the existing route, and the geologic hazards described in this report can either be avoided or mitigated through careful design and construction.

2) Due to the presence of active debris slide complexes along the parts of the alignment originally supplied by NMSHTD, an alternative high route (indicated on the Engineering Geologic Map and Geologic Hazards Map) should be considered. Although the alternative route would be slightly longer and steeper than the route originally proposed by NMSHTD, it would completely bypass the unstable slopes and eliminate the need for expensive and potentially fallible stabilization measures. *Cienegas* on the active debris slides may fall within the statutory definition of wetlands; if so, drainage would be eliminated as a slope stabilization alternative.

3) If, for reasons not related to geology, it is decided to follow the originally proposed route across the active debris slides, then care should be taken to transfer the entire load of the highway to underlying Toreva block deposits via drilled piers, shear keys, or some other structural means. Although embankments constructed with lightweight aggregate would be less destabilizing than embankments constructed of traditional rock and earth materials, it is important to recognize that *any* additional load across the head of an active landslide will be deleterious. It should be assumed that the debris slide mass will be moving away from any highway-supporting structures, and that there will be essentially no lateral earth pressure to help support those structures. The active slides should bear no additional weight. Some engineering solutions, for example, excavation for a free-draining shear key, will probably drain the debris slide *cienegas*, which is not desirable from an environmental point of view.

4) An alternative northeastern river crossing, also indicated on the Engineering Geologic Map

and the Geologic Hazards Map, should be considered. This alternative would shorten the originally proposed alignment by about one-half mile, and greatly reduce the amount of earthmoving that would be required in order to route the new highway around Pilar. Because the stream terrace and talus deposits across the river from Pilar appear to be underlain by Precambrian bedrock, the NMSHTD alignment may require blasting along part of its length. Drilling will be required to estimate the amount of material that would have to be removed by blasting. The alternative river crossing would pass over deposits with questionable debris slide morphology but no evidence of current or recent movement. Both routes would cross the same distance of potentially liquefiable alluvium.

5) The liquefaction potential of deposits labeled "LQ" on the engineering geologic map should be rigorously evaluated using methods such as those summarized by the National Research Council (1985), including a combination of cyclic shear stress testing, standard penetration resistance, and/or cone penetration resistance as part of any detailed geotechnical studies that may be undertaken. The alluvium should be trenched and logged, if possible, in order to explore for evidence of prehistoric liquefaction events associated with moderate to large earthquakes (*e.g.*, Obermeier *et al.*, 1991; Peterson and Madin, 1992; Sims and Garvin, 1992). The discovery of previously liquefied or potentially liquefiable deposits may also justify a probabilistic analysis of liquefaction potential over the design life of the highway. Before any bridge abutments or foundations are designed, it will also be necessary to explore for potentially liquefiable alluvium buried beneath landslide debris.

6) If the alternative high route to bypass active debris slide complexes is not followed, and the road is built across the heads of the active debris flows (which is not recommended), then the liquefaction potential of these deposits should be analyzed for both static and dynamic loading conditions. Also, refer to recommendation 3.

7) The hydrocompactive potential of deposits labeled "HY" on the engineering geologic map should be rigorously evaluated by drilling, undisturbed sampling, and modified consolidation testing as part of any detailed geotechnical investigations that may be undertaken. Any deposits found to be hydrocompactive should be treated either by flooding or dynamic compaction. Due to water supply problems and the cost of pumping water several hundred feet above river level, dynamic compaction will probably be the less expensive of the two alternatives.

8) Care should be taken to manage surface drainage patterns so that runoff is directed away from both hydrocompactive deposits and active debris slide complexes.

9) Exposures of schists and quartzite near river level along the northwestern side of the gorge between Rinconada and the Glenwoody bridge suggest that shallow, albeit highly fractured, bedrock may provide support for the northwestern end of the southern bridge. Neither depth nor rock quality, however, can be estimated solely on the basis of surficial mapping and air photo interpretation.

10) If it is likely that any version of the proposed highway realignment will be constructed in the future, monitoring of slope movements and groundwater conditions should begin as soon as possible in order to better assess the potential for slope instability along the northwestern side of the gorge. Both the obviously active debris slide complexes and the apparently stable Toreva block deposits should be monitored using a combination of piezometers, borehole inclinometers, and surface monuments. Due to the rough terrain and lack of benchmarks, high-precision global positioning system (GPS) methods may provide an effective means of surveying instrument locations and monitoring the displacement of surface monuments. In addition, some attempt should be made to estimate the magnitude, duration, and frequency of precipitation events necessary to destabilize dormant Toreva blocks, and then to estimate the likelihood that these events will occur during the design life of the highway.

11) Adequate instrumentation, such as that described in recommendation 9 10, should be installed to monitor the post-construction performance of both natural and engineered slopes. In addition, bridges and any other large structures along the route should be fitted with tiltmeters in order to monitor any small-scale movements that may threaten structural integrity.

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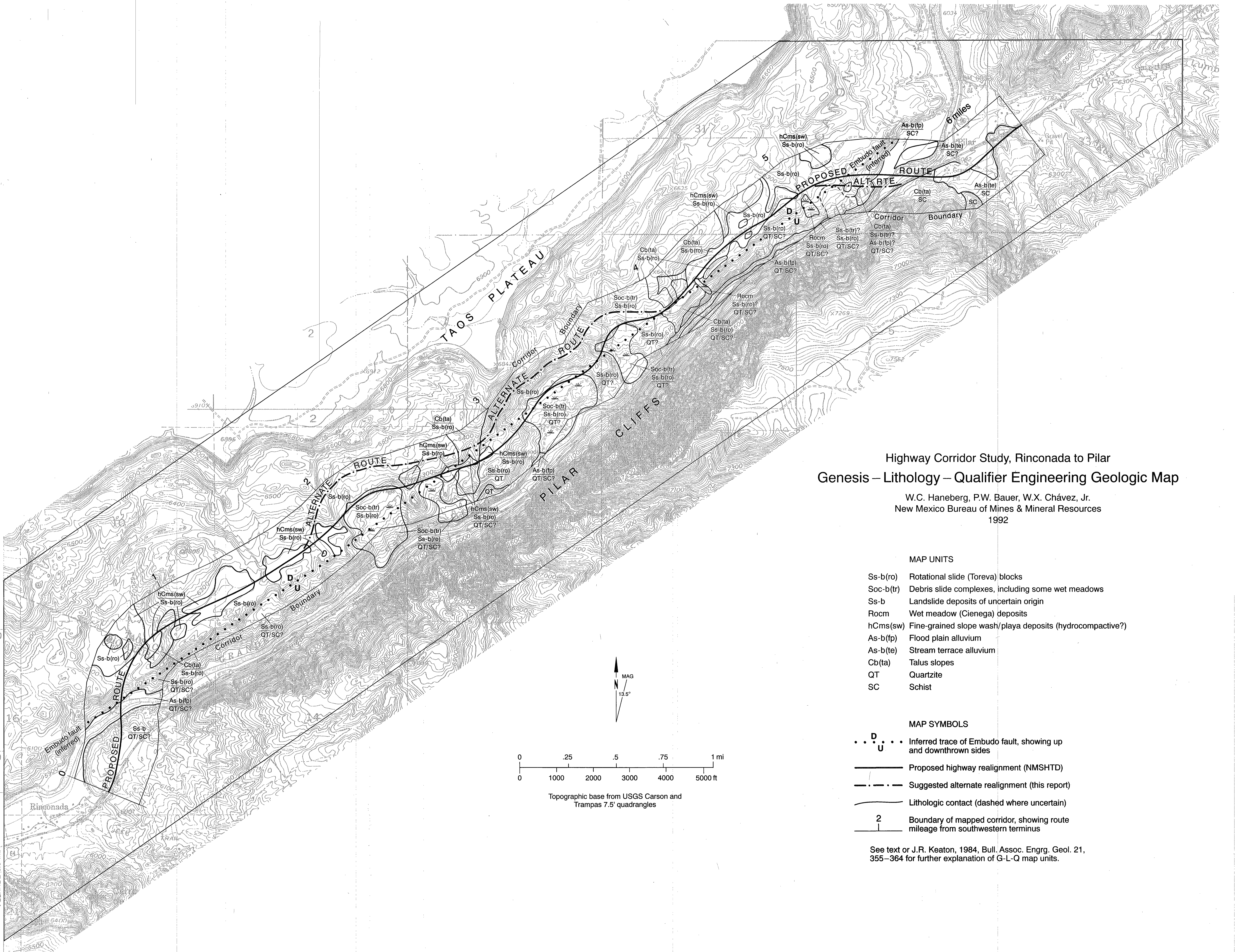
Map 1



Highway Corridor Study, Rinconada to Pilar

Genesis – Lithology – Qualifier Engineering Geologic Map

W.C. Haneberg, P.W. Bauer, W.X. Chávez, Jr.
New Mexico Bureau of Mines & Mineral Resources
1992

MAP UNITS

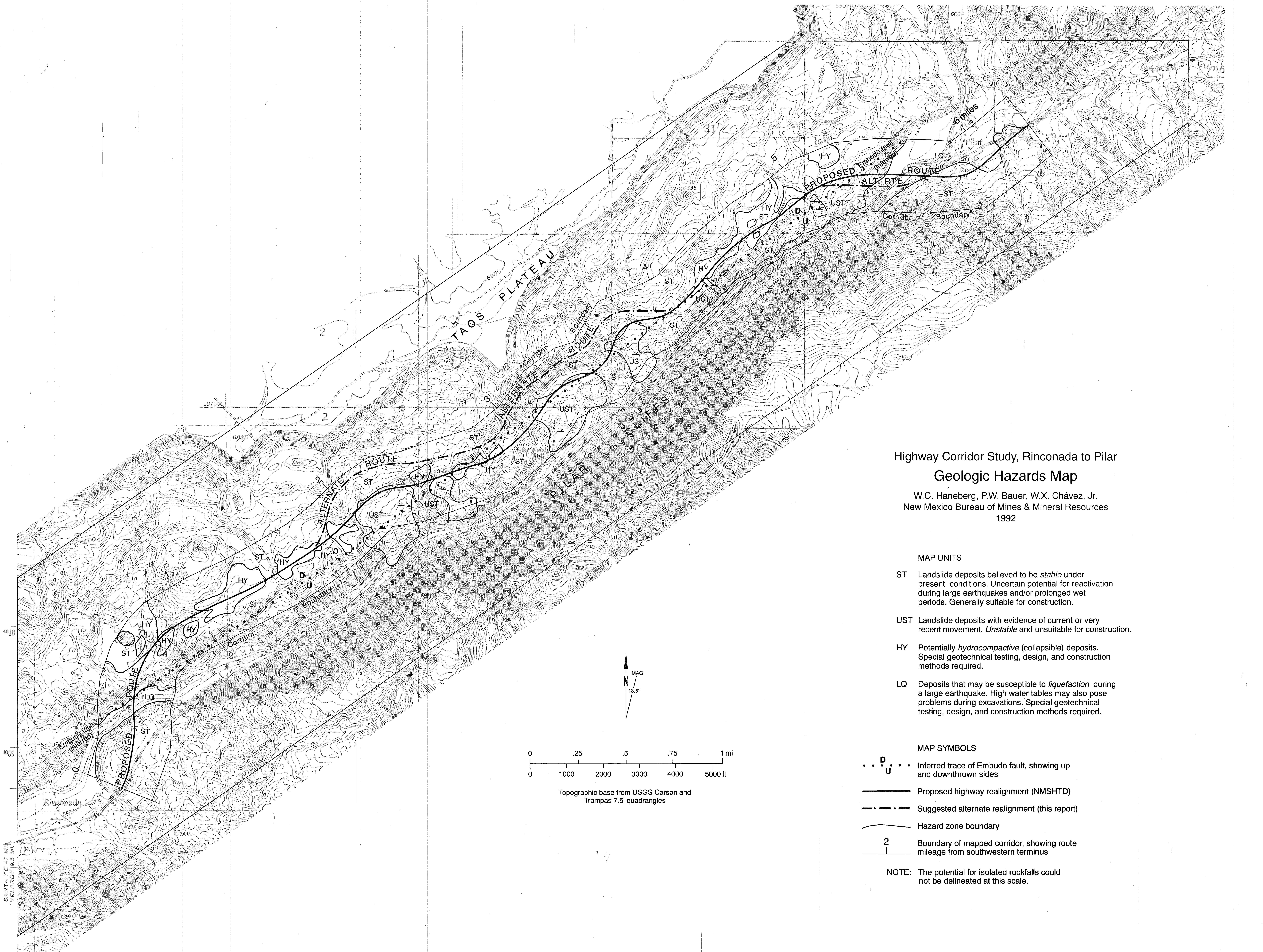
Ss-b(ro)	Rotational slide (Toreva) blocks
Soc-b(tr)	Debris slide complexes, including some wet meadows
Ss-b	Landslide deposits of uncertain origin
Rocm	Wet meadow (Cienega) deposits
hCms(sw)	Fine-grained slope wash/playa deposits (hydrocompactive?)
As-b(fp)	Flood plain alluvium
As-b(te)	Stream terrace alluvium
Cb(ta)	Talus slopes
QT	Quartzite
SC	Schist

MAP SYMBOLS

- Inferred trace of Embudo fault, showing up and downthrown sides
- Proposed highway realignment (NMSHTD)
- Suggested alternate realignment (this report)
- Lithologic contact (dashed where uncertain)
- Boundary of mapped corridor, showing route mileage from southwestern terminus

See text or J.R. Keaton, 1984, Bull. Assoc. Engrg. Geol. 21, 355–364 for further explanation of G-L-Q map units.

Map 2



Topographic base from USGS Carson and Trampas 7.5' quadrangles

Highway Corridor Study, Rinconada to Pilar

Geologic Hazards Map

W.C. Haneberg, P.W. Bauer, W.X. Chávez, Jr.
New Mexico Bureau of Mines & Mineral Resources
1992

MAP UNITS

- ST — Landslide deposits believed to be *stable* under present conditions. Uncertain potential for reactivation during large earthquakes and/or prolonged wet periods. Generally suitable for construction.
- UST — Landslide deposits with evidence of current or very recent movement. *Unstable* and unsuitable for construction.
- HY — Potentially *hydrocompactive* (collapsible) deposits. Special geotechnical testing, design, and construction methods required.
- LQ — Deposits that may be susceptible to *liquefaction* during a large earthquake. High water tables may also pose problems during excavations. Special geotechnical testing, design, and construction methods required.

MAP SYMBOLS

- Inferred trace of Embudo fault, showing up and downthrown sides
- Proposed highway realignment (NMSHTD)
- Suggested alternate realignment (this report)
- Hazard zone boundary
- Boundary of mapped corridor, showing route mileage from southwestern terminus

NOTE: The potential for isolated rockfalls could not be delineated at this scale.