Geothermal Resources Council TRANSACTIONS, Vol. 15, October 1991

CATASTROPIC LANDSLIDE AT ZUNIL I GEOTHERMAL FIELD, GUATEMALA

JANUARY 5, 1991

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ABSTRACT

On January 5, 1991, at 2230 h local time, a catastrophic landslide occurred in the Zunil I geothermal field, in western Guatemala. The area is characterized by high relief, steep terrane, and is located on the flanks of Cerro Quemado Volcano. Active faults permeate the geothermal field, which is well known for its abundant fumaroles and hydrothermally altered volcanic rocks. The slide engulfed an area known locally as *"la calera"*, ("lime-like") that contained active fumaroles as well as the access road and drill pad for well ZCQ-4. Prior to that, *la calera* was the site of small scale prospection for mercury.

The landslide is multi-lobate in shape and is nearly 800 m long; it varies from 200 to 300 m in width. Accurate measurements of thickness are difficult to obtain, but estimates vary from three to ten meters. Twenty-three people were killed in this landslide.

Initial reports by the Associated Press (AP) attributed the slide to an explosion at geothermal well ZCQ-4, which was heavily damaged and buried by the slide. Subsequent reports erroneously stated that an explosion occurred at an unfinished geothermal power plant and compared the blast and tragedy to the 1986 disaster at the Chernobyl nuclear power plant. Press reports in Guatemala were particularly inflammatory and harshly critical of the developers. Statements issued by the Guatemalan govenment agency responsible for the Zunil I project (INDE) and spokesmen for the geothermal industry refuted early press reports and blamed the cause of the landslide on natural causes.

This paper describes an investigation of the landslide that was conducted in Guatemala between January 21, and January 26, 1991. The observations and conclusions represent a team effort and include descriptions of the site geology, engineering geology, and well-head assembly. Underlying factors that may have contributed to slope instability are identified and several components that may have triggered the slide are discussed. Recommendations for the Zunil field and similar geothermal areas are provided.

INTRODUCTION

The Zunil I geothermal field is located in southwestern Guatemala about 8 km south of the city of Quetzaltenango and immediately west of the canyon of the Rio Samalá (Fig.1). The field is developed in a region of rugged topography at elevations of 2000 to 2200 m. The geothermal area contains numerous fumaroles, mud pots, and hot springs and is flanked by Quaternary to Recent volcanoes that form part of the northwest-trending Central American volcanic arc. Exploration and development of the field was initiated by the Instituto Nacional de Electrificacion (INDE) in 1973 and has continued to the present. As of this writing, no electric power is produced at Zunil I, although INDE hopes that a 15 MW(e) power plant will be eventually constructed (Mink et al., 1988; Cordon y Merida Ings., 1988; Foley et al., 1990).

By 1988, several exploration wells and six "production" wells had been drilled to depths of 1300 m. The wells encountered temperatures of 280°C in a liquid-dominated, geothermal reservoir consisting of faulted and fractured Plio-Pliestocene volcanic rocks. Results of an extensive well testing program conducted in 1989 indicated that three wells (ZCQ-3, -5, and -6, Fig. 1) have a combined initial power capacity of 10.8 MW(e) (Cordon y Merida Ings., 1991). The other three deep wells are not considered to be adequate for power production for various reasons. A program of additional drilling began in 1990 to test production possibilities in fractured granodiorite underlying the volcanic rocks.

On January 5, 1991 at 2230 h local time, a large landslide swept southeast across the geothermal field toward the Rio Samalá (Fig. 2), killing 23 people who lived on small farms within the area. The headwall of the slide occurs just west of well ZCQ-4 which was buried when the slide gave way. Newspaper reports on the incident produced confusing and conflicting information suggesting that the slide was caused by an explosion of well ZCQ-4. Because of the fluidized nature of the slide deposits and the large clouds of steam venting from above the damaged well, some local residents believed that the slide was a lava flow. Some of the residents were treated for burns from the hot mud flow.

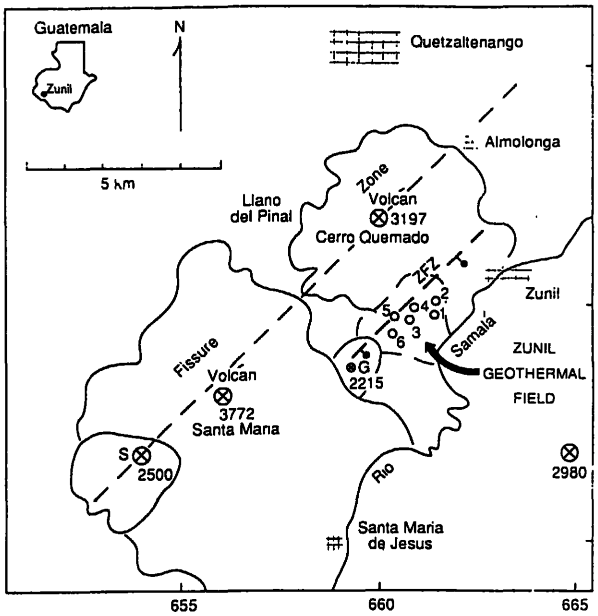

Fig. 1. Sketch map of Zunil I Geothermal Field, Guatemala showing major volcanoes and tectonic features; ZFZ=Zunil fault zone, S=Santiaguito Volcano, G=Cerro Galapago. Numbers by small circles are geothermal production well ZCQ-1 to ZCQ-6. Elevations at volcano summits in meters. Ball and bar on downthrown side of ZFZ. Landslide headwall occurs just west of well ZCQ-4 and ZFZ; slide traveled southeast toward Rio Samalá.

Soon after the slide, INDE conducted an investigation to determine the cause of the slide, to evaluate the damaged well, and to provide security measures for workers and residents in Zunil (INDE, 1991). INDE reported, on the basis of their preliminary study, that the slide was an unfortunate catastrophe caused by natural events. Subsequent published and unpublished reports appear to support the initial INDE report (see Barberi et al., 1991, Cordon y Merida, 1991b, 1991c, and Schaefer and Williams, 1991).

The object of this report is to present the results of a scientific investigation focusing on the factors that contributed to the slide. These factors include, but are not limited to the steep terrane, the proximity of the Zunil Fault Zone, and the active hydrothermal alteration zone. Several trigger mechanisms that may be significant include rainfall patterns and surface water distribution, subsurface water, earthquakes, and the historical and present activities of man (road and drill pad construction). In addition, the testimony of Guatemalans who were present at the time of the slide will be evaluated within the context of the two prevailing theories: an explosion at well 4, or a combination of natural causes.

Fig. 2. Photograph looking WNW showing extent of Zunil landslide.

GEOLOGIC SETTING

Although the Central American volcanic arc surmounts a broad volcanic highland of northwest trend that has been active for the last 15 Ma (Reynolds, 1987), the most striking physiographic feature in the Zunil area is the northeast-trending alignment of Santiaguito, Santa Maria, and Cerro Quemado volcanoes (Fig.1). Santa Maria is a symmetrical, andesite stratovolcano built during the last 30 k.y. (Rose, 1987). In 1902, a sudden explosion formed a large crater on the southwest flank of Santa Maria. From 1922 until present, dacite dome eruptions have progressively filled the crater forming Santiaguito (Stoiber and Rose, 1969). Cerro Quemado is a composite andesite-dacite dome complex that last erupted lava flows in 1818. Other late Pleistocene volcanoes occur a few kilometers to the north and east of the Zunil I geothermal field (Tobias and Quiesa, 1981).

Foley et al. (1990) have presented strong evidence that the subcircular Quetzaltenango depression, located north of the geothermal field, is a large caldera whose southern margin is straddled by the volcanoes described above. No dates have been obtained on tuff units that may have originated from this proposed caldera, but Foley et al. (1990) suggested that tuff units (Green Tuff) of Pliocene age, intercepted by drill holes, were erupted from the caldera. These tuffs are overlain by up to 1000 m of Pleistocene andesitic lavas and breccias in the geothermal field.

The northeast-trending Zunil fault zone (ZFZ) has been identified as a zone of predominantly left-lateral strike-slip motion (Stoiber and Carr,1973), but near the geothermal field it bounds the west side of a graben containing many faults showing normal displacements. The fissure zone that feeds magmas to the Recent volcanoes is parallel to the trend of the ZFZ. Thus, in its broadest sense, the Zunil fault system is a belt of parallel to subparallel structures nearly 10 km wide representing a major northeast-trending crustal fracture (Stoiber and Carr, 1973; Foley et al., 1990).

The ZFZ forms a prominent topographic scarp west of the geothermal field and apparently marks the approximate northwest boundary of fluid production. The ZFZ is also defined by linear zones of relatively low-temperature acid (argillic) alteration, locally containing sulfur and cinnabar, by aligned fumaroles, and by steep gravity gradients.

The top of the Zunil geothermal system contains acid-sulfate hot springs and associated mud pots and fumaroles that occur on high ground on both sides of the Rio Samalá. Bicarbonate-rich hot springs discharge in the canyon of the Rio Samalá. Neutral-chloride fluids, typical of liquid-dominated geothermal systems, are found only at depths > 500 m in the geothermal field (Fournier et al., 1982; Cordon y Merida Ings.,1988; Moore et al., 1990; M. Adams et al., 1990). Production is highly localized along fractures. Variable chemistry and flow test performance between individual wells indicate that the reservoir is chemically inhomogeneous and of rather poor hydraulic conductivity (A. Adams et al., 1990; Cordon y Merida, Ings.,1991).

LANDSLIDE SPECIFICATIONS

The landslide exposed a major trace of the ZFZ on either side of the headwall area (Fig. 3). The fault juxtaposes (brown) weathered to lightly altered hornblende andesite/dacite flow and flow breccia on the northwest (upthrown side) against (white to pink) severely altered and brecciated volcanic rock. The main fault plane strikes N 40° to 45° E, dips 65° to 80° SE, and is sharply defined by gouge, breccia, open cracks, and color contrast. Widely-spaced parasitic fractures of similar strike and dip extend for roughly 60 m to the southeast into the downthrown block. Weak fumarole emissions, smelling of H_2S and visible from steam, discharge from open cracks along isolated locations of the main fault trace and the parasitic structures. Alteration is mainly kaolinitic with minor iron oxides and sulfates caused by oxidation of acid gases, along fractures, and of disseminated pyrite, in the host rocks, to sulfuric acid.

Due to the high degree of hydrothermal alteration and fine-grained nature of some of the volcanic rocks, four samples were collected from the side and head wall of the slide for thin section and x-ray diffraction analysis. The samples include two from the white, highly altered zone , one low on the fault, the other higher up the fault; a relatively unaltered reddish colored volcanic rock; and a greenish colored clay believed to be a hydrothermal alteration product of the andesite/dacite flows.

Thin sections reveal the flow/flow breccia contains phenocrysts of hornblende, plagioclase, orthopyroxene, rare clinopyroxene and opaques in a glassy, flow-banded groundmass containing microlites of mostly plagioclase and opaques. Some plagioclase phenocrysts are complexly zoned, twinned, and embayed. The rock also contains 1 to 3 mm hornblende-pyroxene-plagioclase clots. Locally, this unit is brecciated into volcanic rock fragments, and a paste of secondary clay, iron-oxides, and silica. Pyrite is also observed as a secondary alteration phase.

Table 1 lists the major, minor and trace phases identified and the probable source rock.

Table 1.

X-Ray diffraction analytical results of selective rock samples from the Zunil landslide headwall and sidewall

Sample	Field Description	Major	Minor	Trace	Rock Type
ZUN-01	Hard,chalky-white, fine grained,upper fault zone	Crist. Glass	Alun.	und.	Pyroclastic Volcanic Ash
ZUN-02	Hard,chalky-white, fine grained,lower fault zone	Crist.	Glass Alun.	Tridy. und.	Pyroclastic Volcanic Ash
ZUN-03	Soft,sandy,green clay	Kaolin.	Plag.	Pyrt. Gyps. Amph.	Altered Lava Andesite?
ZUN-04	Reddish-brown, fine-grained volcanic	Kaolin.	Plag.	Amph. und.	Altered Lava Andesite?

Key: Crist.= critobalite, Alun.= alunite, und.= undetermined, Tridy. = tridymite, Kaolin. = kaolinite, Pyrt. = pyrite, Plag. = Plagioclase, Gyps. = Gypsum, Amph. = amphibole.

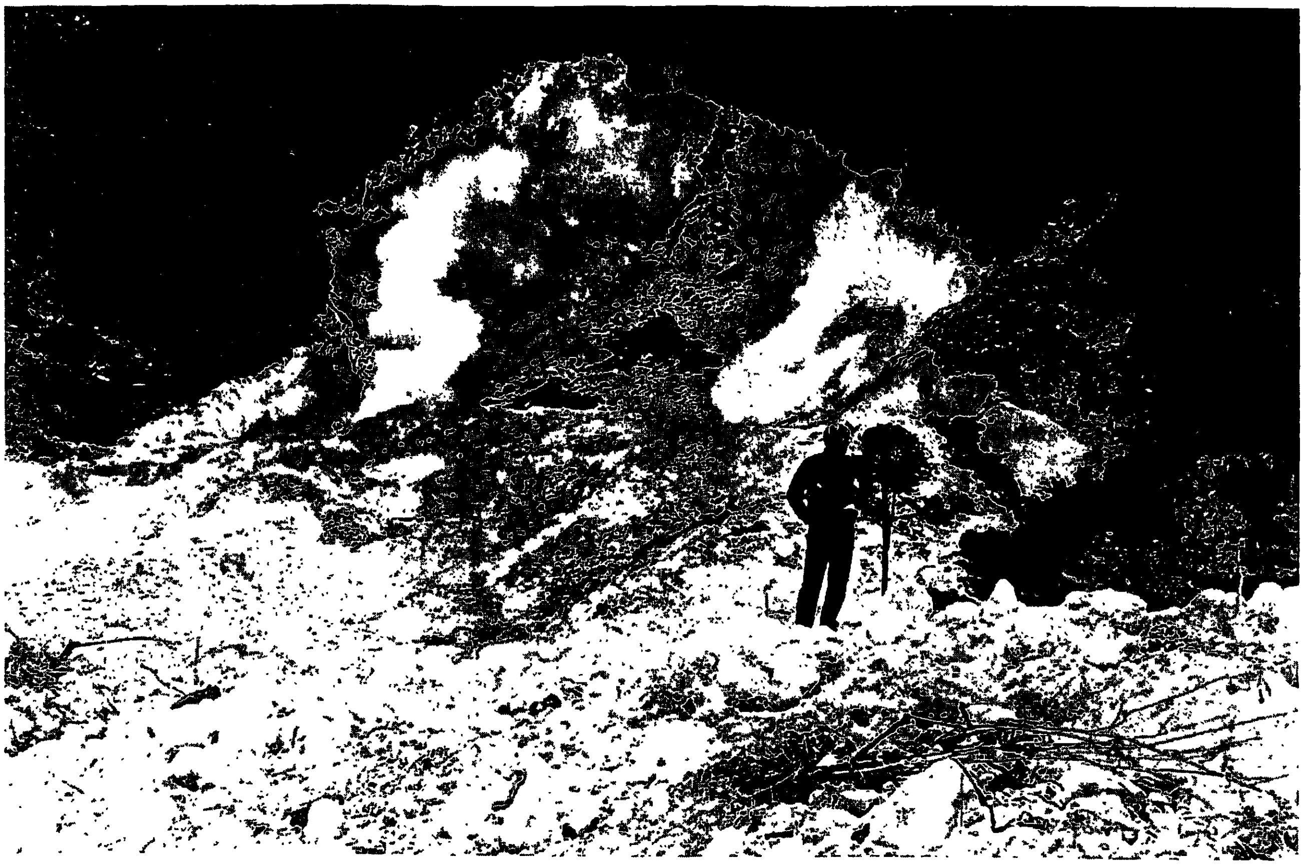

Fig. 3. View of headwall and sidewalls of slide from below crater.

On the basis of these data, two volcanic formations have been identified in the slide area known as *"la calera"*. The first, a hard, white-colored rock, is a silica-rich pyroclastic deposit consisting largely of crystobalite and volcanic glass. Trace amounts of trydimite support this assessment and minor amounts of alunite [$KAl_3(OH)_6(SO_4)_2$], an alteration product associated with mineralization, hot springs and veins, are consistent with fumaroles observed in the area.

The second rock formation, a hydrothermally altered flow/flow breccia, originally contained a mineral assemblage of plagioclase, hornblende and pyroxene. Hydrothermal alteration products include kaolinite, pyrite and gypsum. Most of the advanced alteration occurs within the Zunil fault zone where the soft, green, sandy-clay was collected. No quartz was identified in either sample, suggesting that the original rock was an andesite.

The fault zone is overlain by relatively unaltered and unfaulted volcanic colluvium supporting luxuriant vegetation, thus, the exact fault trace was not identifiable before the slide occurred.

The slide consists of one main lobe of white- and green-colored, highly fluidized, volcanic breccia (Figs. 2 and 4) that moved downslope rapidly as a mudflow. It is this first lobe that buried people alive and cut off the paved road between Quetzaltenango and the Pacific coast. Two to four smaller subsidiary lobes, less fluidized than the first, followed after the initial lobe. A small crater, about 15 m in diameter, developed a few meters downslope of the damaged, buried well ZCQ-4. The crater apparently formed when debris that had buried the damaged well were forcibly ejected by a mixture of hot water and steam that escaped from the well. As the crater was formed a radial blanket of fine-grained mud up to several centimeters thick was deposited around the crater. The crater must have formed late in the sequence of slide events because it is very well preserved. It is likely that the post-slide blast was interpreted as an exploding geothermal well by some of the early observers.

On January 23, 1991, the crater was partially filled with boiling water geysering continuously to 3 m. The crater was breached on the southeast margin and was discharging roughly 20 l/min of water. According to INDE, this water contained approximately 800 mg/kg Cl or about half the salinity of reservoir fluid. Thus, the damaged well was leaking roughly 10 l/min of fluid and was not a "blowout" of major proportions.

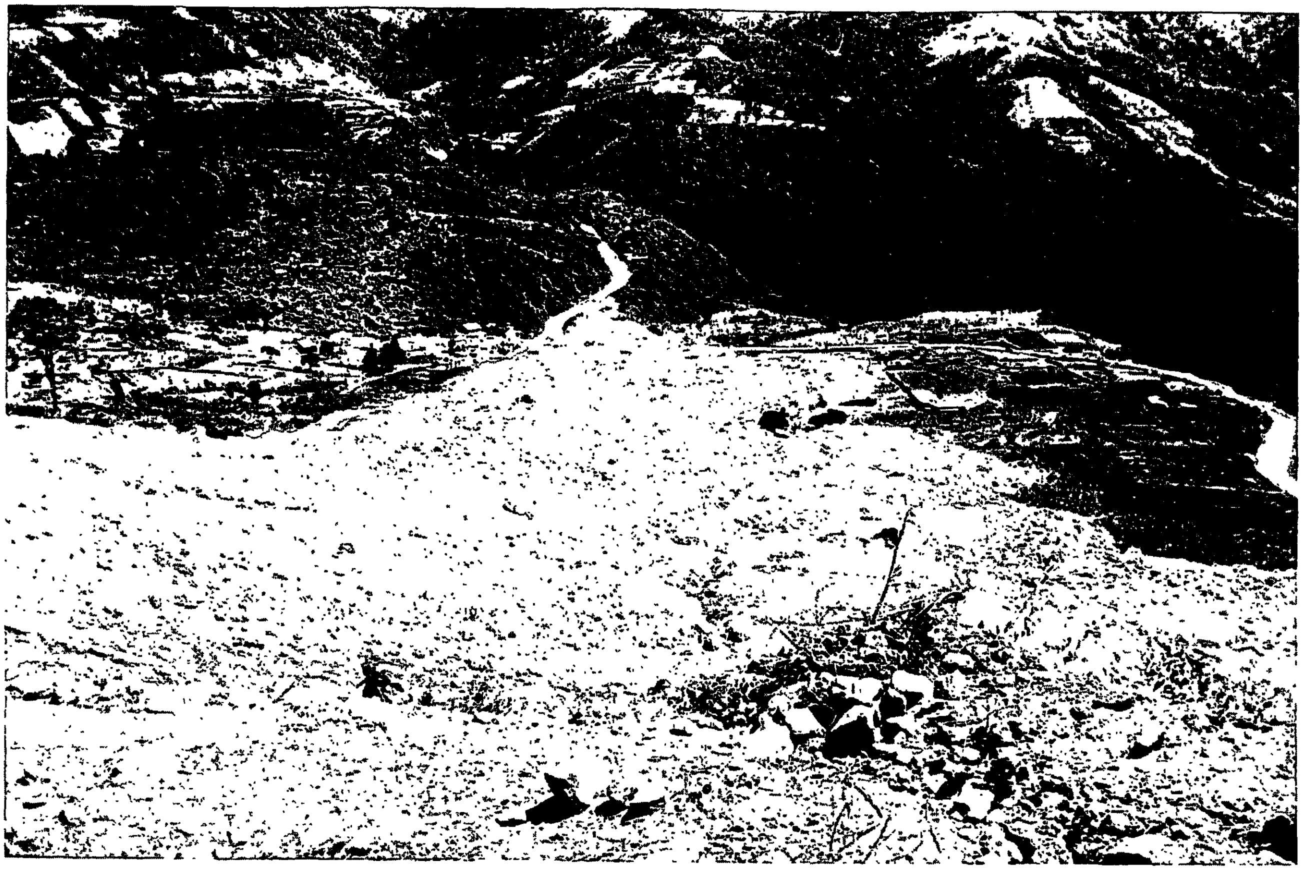

Fig. 4. View looking down the surface of slide from steam crater.

The entire area affected by the slide is shown in plan view in Fig. 5, and a cross section through the slide is sketched in Fig. 6. This information is as accurate as can be obtained without detailed survey data. The volume of the material involved can be calculated from the plan view shown in Fig. 5 (assuming an average thickness) or from the profile view of Fig. 6 (using an average width). An estimated volume of 800,000 m^3 is obtained in this manner. Additional survey data will provide a better estimate of the volume (a slide area of 100,000m^2 with an average 8 m thickness and a profile area of 6,400 m^2 with an average width of 125m were used).

The slide itself exhibits a classical circular failure mode (see Figs. 6 and 7). Slides of this type are commonly described in the literature (see, for example, Taylor, 1948, Hoek and Bray, 1981, Chowdhury, 1987, or Richards and Atherton, 1987). Thus the form of the failure is fairly well known. In fact, the references listed above give means by which to calculate the stability of such a circular failure. However, one has to estimate or determine factors such a density of material, angle of repose (or friction), cohesion of the material, and height of slope (this supposes locating the top of the failure zone). These parameters can be estimated for the material involved in this slide (from Fig. 6 and other data, the natural angle of repose is between 35 and 40°, and the height of slope is about 130m, manifested by the fault trace). Without laboratory tests, the other two parameters would have to be estimated from the literature. If one does that, the safety factor can be determined (defined as the ratio of resisting forces (F_r) to mobilizing forces (F_m), $[(F_r)/(F_m)]$ = SF. Usually, a safety factor (SF) of 1.2 to 1.3 is desired. Clearly, the safety factor here was near or slightly below 1.

PRODUCTION WELL ZCQ-4

Well ZCQ-4 was drilled in 1981 to a depth of approximately 1,300 m. The well is cased (with 24 cm diameter casing) and cemented to a depth of 440 m. A liner (19 cm diameter) is hung from the casing to the bottom of the well. The well-head testing equipment was removed prior to the slide. The remaining well-head assembly consisted of an expansion spool and a 27 cm master valve, all of which was contained within a 2 m by 3 m by 3 m (deep) concrete cellar. The cellar was partially covered with steel rails, to protect the well head equipment from rock falls. In October, 1989, the recorded bottom hole temperature was 260°C (Cordon y Merida Ings., 1989)

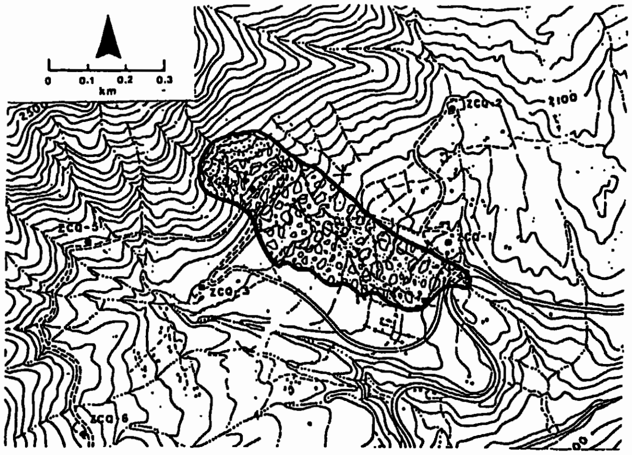

Fig. 5. Plan view of slide area

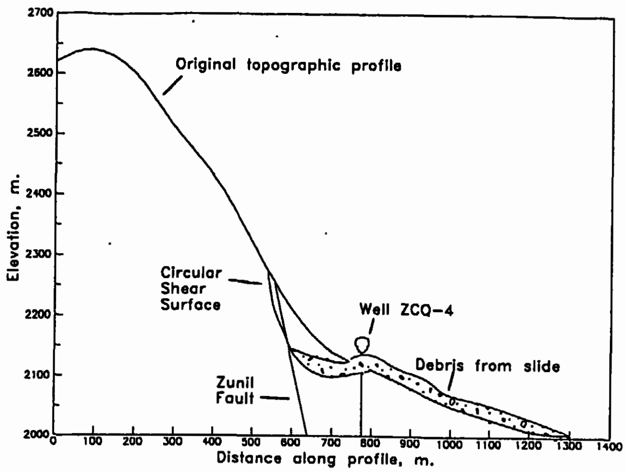

Fig. 6. Profile view of slide, looking northeast

Following slope failure and the subsequent landslide, the well head was apparently ruptured and covered by an estimated two to three meters of debris. The rupture is manifested by a continuous cloud of steam erupting with hot water and small rocks from a crater, 15 meters in diameter, in the slide, which is approximately eleven meters downslope from the original well head location. The volume and intensity of the flow of water and steam is small compared to the potential full-bore flow of 20 to 30 tons/hour. If the well-head were either blown off in an explosion or sheared off in the landslide, the flow would be much greater.

Although the well-head remains buried, the burial depth is shallow and the material is unconsolidated. Assuming a shut in pressure of 400 psi, this well should be violently blowing out of control. A significant amount of vapor is evident in the steam plume, but total mass flow is small. It is unlikely, therefore, that the well head or casing are entirely severed. The small flow suggests that the casing is cracked or a small valve is leaking.

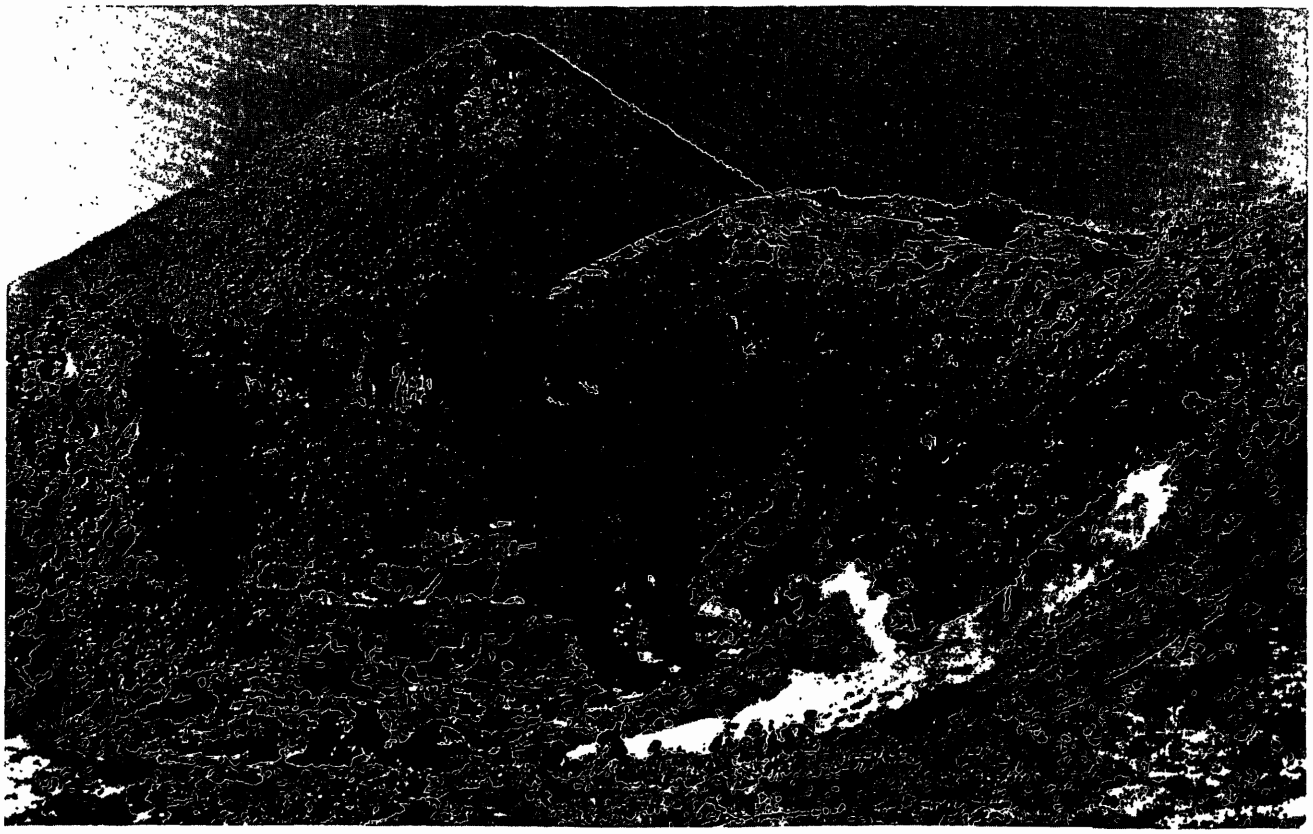

Fig. 7. Profile view of slide, from the northeast looking southwest.

CAUSE OF THE SLIDE

Landslides, in general, occur as a result of a combination of contributing factors. In Zunil, the three major factors that contributed to the slide were massive amounts of weak, hydrothermally altered rock, the proximity of the Zunil fault zone, and the very steep topography.

Throughout the Zunil area, recent volcanic rocks are covered by a thin veneer of alluvium, colluvium, pumice deposits, and landslide debris. Argillic hydrothermal alteration is broadly distributed in the upper 100 to 200 m of each well in the Zunil I geothermal field. Kaolinite and alunite identified in x-ray diffraction patterns show that the andesites and pyroclastics in the headwall and sidewalls of the slide were both subject to varying degrees of hydrothermal alteration.

The Zunil fault has been described as a northeast-trending, predominantly left-lateral, strike-slip fault (Stoiber and Carr,1973). It is defined by linear zones of relatively low-temperature alteration, by the alignment of fumaroles, and by steep gravity gradients. A portion of the fault is exposed in the headwall.

Topographic relief in the valley is extreme; measured slope angles in the vicinity of the slide range from 30° to 50°. The angle of the slope prior to the slide was about 35°. These slope angles approach and exceed the angle of repose for most dry, unconsolidated material.

Together, these three underlying factors would have eventually produced a landslide in the area. Very often, however, slopes can exist in a state of unstable equilibrium for extended periods of time. Vibrations from external sources may provide sufficient energy to trigger a slide. Blasts, associated with construction activities, and vibrations from heavy trucks have been credited with initiating some landslides in prone areas. No unusual activities were reported in the vicinity of the slide and Guatemalans who were present at the time of the slide testified that they heard no explosions prior to the slide. Earthquakes are also known to trigger events in slide-prone areas. A small earthquake was reported to have occurred 60 km west of Zunil approximately six hours before this slide, but was not felt in the area.

The fluidal texture of the surface of the slide indicates that the debris material was at least partially saturated with water. The addition of water increases the weight of the potential slide material and decreases the frictional resistance along the failure plane by increasing the pore pressure. Additionally, this moisture can lower the cohesion of certain clays, particularly semectites which expand when wet. Since the increased fluid content may have triggered the slide, the origin of this additional moisture is a key element in the resolution of the cause of the slide.

Annual precipitation in Zunil is approximately 900 mm per year and the rainy season extends from May through November. There are no reports of unusual amounts of precipitation during the previous rainy season and there is no record of rain either prior to or during the landslide. The effects of a surface water contribution to the instability of the slope appear to be minimal at this time.

Saturation of debris material by subsurface waters may occur by groundwater flow, thermal or non-thermal, or by the condensation of fumarolic vapors. Both are present in the immediate vicinity of the slide, but fumaroles appear to predominate the area. Within two weeks of the slide, fumaroles had been re-established along the ZFZ below the headwall. Koide et al. (1963), report as many as 100 slope failures have occurred throughout Japan in fumarole areas with steep terrain and hydrothermal alteration. In general, these landslides were characterized by rapid, unexpected movement and a change in warm spring activity as a precursor to the slope failure. Testimony from Guatemalans who were working in the area prior to the slide confirm that the spring flow increased and color changed drastically after a smaller landslide occurred behind well number 4 on December 28, 1990.

An additional factor that may have contributed to the instability of the slope is the activity of man in the vicinity of well ZCQ-4. It has been stated that *la calera* was the site of mercury prospecting. The area was serviced by a road, which had to be widened to accommodate the drilling equipment that was used in 1981 to complete well ZCQ-4. This road also provides access to wells ZCQ-5, ZCQ-6, and ZD-1. Although some of the slope material was removed when the well pad was constructed, the affected area was small compared to the slide itself. In addition, these activities took place at least 10 years before the slide occurred. These factors should not be ruled out from consideration, but should be evaluated with respect to the other underlying factors.

On the basis of the preliminary investigation, the most probable cause of this slide is a combination of natural causes that includes at least three underlying factors: steep terrain; weak, altered rock; and the nearby fault zone. The addition of groundwater, either by warm spring flow or fumarole condensation in the near surface, triggered the already unstable slope and caused the slide.

CONCLUSIONS

Until the geothermal well (ZCQ-4) is excavated, there will still be some uncertainty associated with the cause of this tragic landslide. The exploding well theory, however, cannot be substantiated at this time and appears to be an inadequate explanation for the size, shape, and composition of the landslide. The most probable explanation that can be provided from this preliminary study is that the slope behind well ZCQ-4 was in a state of unstable equilibrium with a safety factor equal to or slightly less than 1. Contributing to this condition were the steep terrain, the abundant hydrothermally altered rock, and the proximity of the Zunil fault zone. The parameter that moved the safety factor even lower was increased moisture in the slope. This came from either increased spring flow, increased fumarole activity or some possible subsurface leak in the casing of well ZCQ-4. Although earth tremors and explosions can trigger slides, there are no reports that these activities occurred in the Zunil area the night of January 5, 1991.

RECOMMENDATIONS

The fundamental problem in the investigation of landslide hazards is the inability to forecast the occurrence of the phenomena accurately in all slide-prone areas. In the Zunil geothermal area, the very steep topography alone strongly suggests that more landslides will occur throughout the valley. As geothermal development continues, it would be appropriate for the industry to adopt a systematic approach to hazards reduction. With that in mind, the following recommendations are submitted:

1. Complete a detailed surficial geology and slope stability map at 1:10,000 scale showing talus, colluvium, landslides, alteration zones, faults, fractures, etc. and the relative ages of these features with a ranking of hazardous locations.

2. Springs in the slide area should be monitored more closely because changes in chemistry, temperature, flow rate, and clarity may indicate danger situations. Since groundwater is one of the major contributing factors in landslides and slope failures, periodic measurements of water levels would be indispensable to understanding the mechanism of the slide.

3. In the vicinity of the present slide, an extensive network of electronic distance measuring (EDM) stations, that will monitor movement, should be installed. One can always predict a slide before it happens if the proper network is operating. Descriptions of such networks are given in Larocque (1977) and Hanna (1985).

4. Drill pads and power plants should avoid sites of obvious potential hazard such as altered ground, fault traces, and steep scarps, and obvious young slides.

5. Since the addition of water is the greatest destabilizing factor for an existing slope, the best means to prevent failures such as this is the installation of a drainage system to "dry out" the slope.

6. In terms of the slide under discussion, there are three things that should be done before deciding to uncover well no. 4: a detailed topographic survey of the slide area should be performed, the existing damaged slope should be assessed carefully for loose material and that material should be blasted down or bolted to protect workers below, and then 2 to 4 shallow wells should be drilled near well no. 4 to predict where the slip circle actually intersects the well. It is not easy to predict the condition of the wellhead, and this information is crucial to assessing the safety of any uncovering operation.

Since the development of geothermal resources is likely to continue in areas similar to Zunil, Guatemala, it is appropriate that the lessons learned here be applied to geothermal projects throughout the world.

ACKNOWLEDGMENTS

We wish to thank our colleagues in Guatemala for their very competent assistance, and for their friendship: Andres Caicedo, Oscar Castaneda, Otto Garcia, and Carolina Grajeda of INDE, and Tomas Hirschmann and Sergio Aycinena of Swissboring Overseas Ltd. Thanks also to Keith Stever of the Reno Research Office of the U.S. Bureau of Mines for the x-ray diffraction work. Thanks also to the thoughtful and wise gentleman who both conceived of and sponsored the project.

In conjunction with this report, and in response to the unbalanced treatment of this tragedy by the International Press, a video documentary was produced by the University of Nevada, Las Vegas, Environmental Research Center, Division of Earth Sciences that focuses on the factors that contributed to this slide. This professionally produced video tape is 22 minutes long and has been distributed throughout the world by UNLV. The authors would like to acknowledge John Foss and *StoryBoard Productions* for all the hard work and long hours that went into the video shooting, post-production, editing, and audio portions of the program. We couldn't have done it without you. For information on how to obtain a copy, please write to Thomas Flynn, Division of Earth Sciences, 100 Washington St., Suite 210, Reno, NV 98503.

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