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Landslides and the weathering of granitic rocks

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ABSTRACT

Granitic batholiths around the Pacific Ocean basin provide examples of landslide types that characterize progressive stages of weathering. The stages include (1) fresh rock, (2) corestones, (3) decomposed granitoid, and (4) saprolite. Fresh granitoid is subject to rockfalls, rockslides, and block glides. They are all controlled by factors related to jointing. Smooth surfaces of sheeted fresh granite encourage debris avalanches or debris slides in the overlying material. The corestone phase is characterized by unweathered granitic blocks or boulders within decomposed rock. Hazards at this stage are rockfall avalanches and rolling rocks. Decomposed granitoid is rock that has undergone granular disintegration. Its characteristic failures are debris flows, debris avalanches, and debris slides. Saprolite is residual granitic rock that is vulnerable to rotational slides and slumps. As a granitic rock mass progressively decomposes, the critical slope angle decreases, allowing slope failures throughout its weathering history. Failures in granitic rock are more abundant during the advanced stages of decomposition. Therefore, landslides are most common in the humid tropics, where intense chemical weathering occurs. Identification of the granitoid's weathering stage will help the engineering geologist evaluate the slope-stability hazards of an area.

INTRODUCTION

Granitic rocks are not associated with landslides in the minds of most people, yet huge and numerous slides have occurred in some granitic areas. Batholiths surrounding the Pacific Ocean basin provide good examples of landslides in granitic rocks. These batholiths are associated with active subduction zones; therefore, the granitic terranes are relatively young and topographically rugged. Granodiorite is the predominant rock type of these plutons, and true granite is rare (Roddick, 1974). Granitic masses are relatively resistant to decomposition, so they commonly occur as mountainous erosional remnants. Nevertheless, granitoids undergo progressive physical, chemical, and biological weathering that weakens the rock and prepares it for mass movement. Rainstorms and earthquakes then trigger slides at susceptible sites.

The minerals of granitic rock weather according to this sequence: plagioclase feldspar, biotite, potassium feldspar, muscovite, and quartz. Biotite is a particularly active agent in the weathering process of granite. It expands to form hydrobiotite that helps disintegrate the rock into grus (Wahrhaftig, 1965; Isherwood and Street, 1976). The feldspars break down by hyrolysis and hydration into clays and colloids, which may migrate from the rock. Muscovite and quartz grains weather slowly and usually form the skeleton of saprolite. Some granitoids undergo hydrothermal alteration, but this review of the literature does not specifically consider them.

The physical appearance and properties of granitic rock change as weathering progresses. Several investigators have divided the transition into stages (Ruxton and Berry, 1957; Deere and Patton, 1971; Clayton and Arnold, 1972). This paper uses a four-stage classification of weathering products (Fig. 1): (1) fresh rock, (2) corestones, (3) decomposed granitoid, and (4) saprolite. All four stages may exist on an individual slope, but geographically the later stages of weathering increase in occurrence where there are high temperatures and ample precipitation. Fresh rock contains a maximum of 15% weathered material that forms in the joint system. The corestone stage ranges from 15 to 85% weathered rock enclosing remnants of fresh rock. Decomposed granitoid consists of 85 to 100% weathered disintegrated rock that can be broken down into granules. Saprolite is a fine-grained residual rock that generally has an upper lateritic layer.

FRESH ROCK

The susceptibility of fresh bedrock to rockfalls, rockslides, or block glides depends upon a number of conditions, includ-

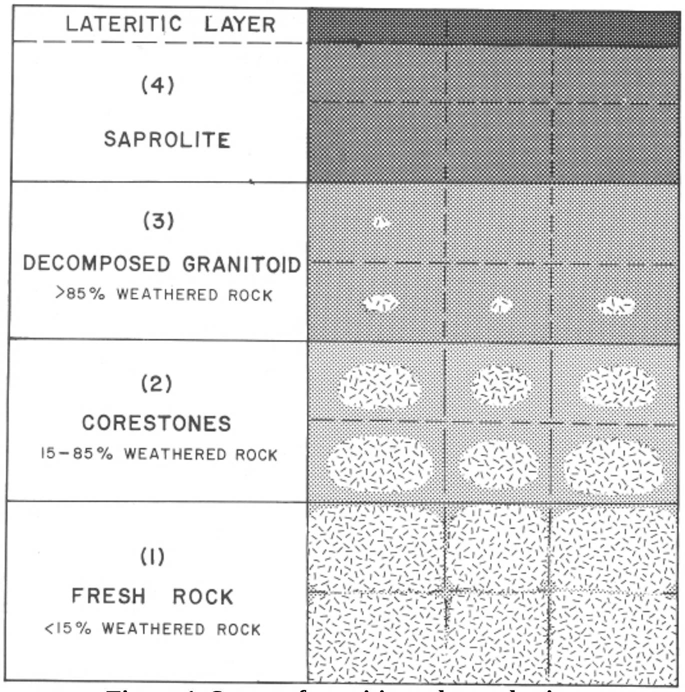

Figure 1. Stages of granitic rock weathering.

ing (1) the angle of shearing resistance of the jointed rock, (2) the effective cohesion, and (3) the seepage pressures of water in the joints (Terzaghi, 1962b). A simple but useful method of studying rockslide occurrence is to consider only the angle of inclination of rock joints. The critical slope angle for rocks with a random joint pattern is about 70° (Terzaghi. 1962b), but sheeting in granite often creates joints that are subparallel to the ground surface, with critical slope angles as low as 30° to 40°. Slabs of sheeted granite may slide down a slope as block glides (Terzaghi, 1962a). As weathering progresses, decomposed granite forms along the joint planes and decreases the effective cohesion while increasing the void ratio. Ground water seeps through these permeable zones (Le Grand, 1949) and generates hydrostatic pressures in the joints.

The Emerald Bay landslide, bordering Lake Tahoe in the Sierra Nevada of California, has undergone two rockslide avalanches and occasional rockslides. The failure originated in fresh granite having fracture planes dipping 30° to 40° downslope toward the lake (McCauley, 1975). The first rockslide avalanche is attributed to road construction across the slope; the second was triggered by a period of very high rainfall. In contrast, the rockslide avalanche of Cerro Condor-Seneca in Peru occurred on a slope of 37° during an abnormally dry season (Snow, 1964). That slide apparently was triggered by desiccation and cracking of the clay joint fillings in the granodiorite.

Debris avalanches or debris slides can occur when fresh granite is near the surface and is covered by organic debris, colluvium, or soil (Fig. 2). Smooth-surfaced granite can reduce the effective friction angle with the overlying material. In additon, water flows through the thin permeable zone above the fresh bedrock, producing pore-water pressures and seepage forces during rainstorms. This process has been observed in steeply sloping forest soils of British Columbia and Alaska, where piezometric levels approached the ground surfaces during periods of high rainfall or snowmelt (O'Loughlin, 1972; Swanston, 1967).

Debris avalanches and slides on fresh granite have also been noted in the Eastern United States, particularly in the Appalachian Blue Ridge Mountains (Williams and Guy, 1973; Scott 1972), and in the White Mountains of New Hampshire (Flaccus, 1958; Pirsson and Rice, 1911).

Evidence of rockslides and rockfalls is common in the geologic record. Talus and scree slopes are accumulations of rock debris that originated with rockfalls or rockslides

CORESTONES

The weathered zone develops outward from the joints and isolates blocks or boulders of fresh rock to form corestones. In some areas, corestones become remnants on the ground surface and may roll down slopes during rainy periods, causing extensive damage (Barata, 1969; Da Costa Nunes, 1969). The type of slide most characteristic of this weathering stage is the rockfall avalanche. It consists of a large rock mass that falls off a steep slope, generating a stream of fast-moving debris. Earthquakes commonly trigger this type of slide by dislodging the partially decomposed rock.

Slide Mountain in Western Nevada offers an example of a rockfall avalanche in granodiorite (Thompson and White, 1964). Intermittent slides have occurred at the scar on this mountain since Pleistocene time. The bedrock has been crushed extensively, and joints dip parallel to the slope. The composite slide consists of about 96,000,000 m^3 of debris—one of the largest on record.

The Mount Huascaran slide in Peru showed that if population centers are in the path of a rockfall avalanche, the results can be catastrophic. The Peruvian earthquake of 1970 —the greatest disaster in the history of the Western Hemisphere - killed about 70,000 people. The quake triggered a slide off a cliff face of partially weathered granodiorite. A stream of debris sped down the valley at 400 km/h, killing 2,000 people in one town and 19,000 in another. Eyewitnesses reported that the debris swept downslope "with a deafening noise and was everywhere accompanied by a strong turbulent airblast" (Ericksen and others, 1970). Browning (1973) concluded that because of its high velocity and movement as a single mass, the Mount Huascaran slide must have moved almost without friction over an air cushion. Arguing against this interpretation, Hsü (1975) suggested that the granitic blocks were dispersed in a dense interstitial mud and flowed down the valleys.

Some deposits of rockfall avalanches are identifiable in the rock record. For example, granitic breccia of a massive landslide that occurred during Miocene time was found in the Las Vegas Valley of southern Nevada (Longwell, 1974). The landslide debris from Slide Mountain still can be seen. The deposits indicate the number of slides, and their degree of weathering provides a clue to the time of their occurrence.

DECOMPOSED GRANITOID

At the stage of decomposed granitoid, granular disintegration takes place, and crystals become increasingly detached from each other. Erosion of the material produces grus. Rainstorms usually bring on the failures that generate debris flows and debris avalanches, although dry debris slides also take place. The most widespread slide problems have been reported at this stage.

The biotite and feldspar weather first, causing microfrac tures and pores to form. Ground water can then leach out the resulting colloids and clays. As the granitoid decomposes, it decreases in bulk density and shear strength (Matsuo and others, 1968). A saturated decomposed granite has essentially no cohesion. Its angle of internal fraction depends on the grain-size distribution, but for design purposes it is assumed to be about 35° (Lumb, 1962; Gonsior and Gardner, 1971).

The weathering front in granitoids is abrupt, and water can be perched above the fresh impermeable bedrock. Subsurface water drains through the decomposed granitoid above the fresher rock. The seeping water removes very fine particles by solution and mechanical eluviation (Ruxton and Berry, 1957; Ruxton, 1958). After rainfall, seepage forces can be especially strong on steep slopes, contributing significantly to instability. Although seepage forces are usually neglected in analyzing slides by the infinite-slope method, Hartsog and Martin (1974) included them in their computer program for landslide prediction. Their analysis was specifically designed for granitoids of the Idaho batholith.

The degree of saturation of the decomposed granite is also important when the factor of safety is about one. When saturation reaches 100%, the apparent cohesion is zero, and pore-water pressures may cause failure. If the material is dry, however, the apparent cohesion is also zero, and dry sliding may follow. Dry debris slides occur on the granitic batholiths of southern California and are particularly common after summer wildfires (Krammes, 1965). Masses of decomposed granitoid slide into ephemeral stream channels, and debris flows may remove them during heavy winter rainstorms. These flows surge down channels and can cause extensive damage to homes (Scott, 1971).

Figure 2. Debris avalanche on fresh granitoid near Sawyers Bar, California. Water is flowing on surface of rock.

Shallow debris avalanches have occurred in the Klamath Mountains batholiths of northern California and southern Oregon (Fig. 3). Tree roots growing in the decomposed granitoid help stabilize the slope. At some sites, rainstorms have triggered failures a few years after roadbuilding and clearcutting of forests.

Japan has undergone recurring disasters in its granitic areas. During such events, landslides and surface erosion injected slugs of decomposed granite (*masa*, in Japanese) into rivers. One such disaster occurred in 1964 at the Kamo-Daito area on the island of Honshu. A map of the weathering stages for this area shows that the landslides were concentrated in the decomposed granitoid and the saprolite (Oyagi, 1968). The decomposed granitoid had a type of immunity to failures once slides had occurred, because the weakest material failed and stronger ones remained. The saprolite had the potential for repeated landslides since the failures exposed rock having a low shear strength. The mapping also indicated that the depths of weathering stages were related to long-standing erosional base levels. Weathering continued to penetrate the rock until it reached the elevation of nearby streams.

Rio de Janeiro, on the east coast of South America, also provides examples of failures in decomposed granitoid. The city's highest recorded rains fell in the summer of 1966 and 1967. These storms resulted in tens of thousands of landslides on bedrock that is predominantly gneiss and granite. The landslides devastated a large area, and in one village about 1,000 people were killed. Jones (1973) concluded that the storm laid waste to "a greater landmass than any ever recorded in geologic literature." He provided striking photos as evidence.

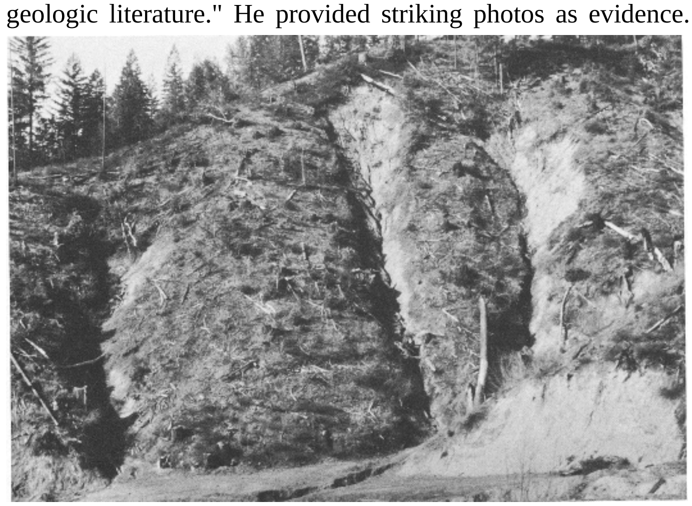

Figure 3. Debris avalanche in decomposed granitoid near Sawyers Bar, California.

Although several types of failures such as rockslides, rockfall avalanches, slumps, and rapid creep occurred, debris avalanches and debris flows were particularly pronounced (Barata, 1969). The thin decomposed mantle was commonly stripped off the slope to form a herringbone pattern in some areas and large shallow scars in others.

Earthquakes can effectively trigger shallow debris avalanches in decomposed granitic material. A statistical analysis of slides in the Bewani and Torricelli Mountains of New Guinea indicated that the distribution of failures in granitic rock was directly related to the epicenters of two earthquakes with magnitudes 7.9 and 7.0 (Simonett, 1967).

Landslide debris associated with this weathering stage is rarely found in the rock record because decomposed granite is highly erodible. Surface erosion produces gullies in the failure scars and discharges grus into the river system. Therefore, it is difficult to determine if a deposit of decomposed granite is the result of mass movement or surface erosion.

SAPROLITE

The final stage of weathering results in a whitish to brownish saprolite overlain by a red lateritic layer, which develops deeper with time. Residual granitoid consists predominantly of quartz, muscovite, and kaolinite. The void ratio increases until overburden pressures force the pore spaces to decrease as the rock compresses. This advanced stage of weathering is most common in the tropics, but it even occurs in the Klamath Mountains and other forested temperate regions, where leaching of the rock is more important than surface erosion.

A slope failure characteristic of saprolite is the slump or rotational slide. The rupture surface is no longer controlled by a fresh rock boundary as in earlier stages, but forms a circular failure surface. Ground water drains through the failure surface and relict joints, precipitating iron and manganese. The shear strength of these seams is usually one-half to two-thirds that of the saprolite (St. John and others, 1969). This type of landslide is most suited to traditional slope-stability analyses that assume rotational failures. Therefore, engineering geologists can usually determine the factor of safety for specific slopes in residual rock.

The degree of saturation strongly affects the strength of residual granitoid. In unsaturated saprolite the apparent cohesion can be as high as 2,000 g/ cm^2, but it will drop to zero when saturated (Lumb, 1965). At some construction sites, deep cuts have encountered the water table in residual granitoid and produced rotational slides (Deere, 1957). Ground water can seep out at the base of the slope, causing piping that undermines the slope. The saturated cohesionless material has little shear strength, and failures may occur in the saprolite as well as along joint planes.

Parts of Rio de Janeiro have rotational slides in saprolite, but man usually contributed to their occurrence (Barata, 1969). Residents of the city destabilized slopes by excavating saprolite, adding surcharges to the tops of hills, and removing man-made structures that provided support to the slopes. When the heavy rains fell in 1966 and 1967, failures occurred in areas that had been made marginally unstable.

Hong Kong is underlain by a mantle of residual granitoid that is about 30 m thick (Lumb, 1965). A rainstorm in 1966 caused the most disastrous mass movements ever recorded in that area (So, 1971). The large, deep-seated failures involved rotational sliding and slumping. Observers reported that a great deal of subsurface water emerged from the slope coincident with failure. So (1971) inventoried the mass movements and concluded (99% confidence level) that they occurred in greater numbers in woodlands than in other types of vegetation. The tree roots probably had no stabilizing effect on deep slides. In addition, woodland soils have infiltration capacities that conduct rainfall to the subsurface rather than allowing overland flow.

Topographic evidence for ancient slumps and rotational slides is commonly observable in aerial photos. If the saprolite is excavated, slickensides in seams of iron and manganese provide evidence of past movement.

DISCUSSION

The number of landslides in granitic rocks compared with other lithologies depends on factors that promote decomposition, such as climate and erosional history. The humid tropics is the site of the most intense chemical weathering, and as a result many of the problem areas in granitoid, such as Hong Kong and Rio de Janeiro, are also within that zone. Rhodes (1968) compared the landslides in granitic rock to ten other lithologies in humid tropical New Guinea. He found that silicic igneous rocks had the most landslides per unit area. On the other hand, Radbruch and Crowther (1973) indicated that in California, granitoid has one of the lowest rates of slope failure of any rock type.

The engineering properties of granitic rock change as weathering continues. Granitoids break down progressively from massive blocks to a deep layer of clay-size particles. Therefore, the disciplines of both rock mechanics and soil mechanics are useful for investigating the slope stability of such materials. The shear strength and critical slope angle decrease as a granitic rock mass weathers. Merritt (1972) described how knowledge of the characteristic critical slope angle at each weathering stage was helpful in a construction project on intrusive rock in Colombia.

Man is more influential at the later stages of granitic weathering because he makes greater use of the gentler slopes, and he can excavate the material more easily. Each stage of weathering is susceptible to specific slope-stability hazards. If the stage of weathering is identified at a site, it will provide clues to the engineering properties of the material and help the engineering geologist predict the slope-stability hazards of proposed actions.

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