USE OF SEISMIC REFRACTION TO DETERMINE THE INFLUENCE OF MICROCLIMATIC ZONES ON THE DEPTH OF WEATHERING ACROSS THE LA POSTA PLUTON

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SAN DIEGO STATE UNIVERSITY

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CHAPTER I

INTRODUCTION

The La Posta Pluton is an ideal subject for a study of the relationship between climate and the depth of granite weathering (Figure 1). The pluton is exposed at the surface extending across three microclimatic zones: Mediterranean-hot summer, semi-arid, and arid (Figure 2). The purpose of this study is to assess the influence of microclimates on the development of soils, character of saprolites, and overall depth of weathering.

The response of granites to weathering has been well documented (Isherwood and Street 1976, Schloten 1997, Twidale 1982, and White et al., 2000). Furthermore work regarding the influence of plants (dependent on climate) on rock weathering (Alexandre et al., 1997, and Moulton and Berner 1998) suggests that a correlation exists between climate and weathering style. Various workers have focused on the effects of climate and weathering. Working in a semi-arid climate, Canton et al. (2001) determined that areas of bare or low vegetation had the highest runoff coefficients and highest erosion rates. In addition, Canton et al. (2001) suggested that most rainfall events within this climate were below the threshold for erosion. Le-Pera and Sorriso-Valvo (2000) described the influence of a Mediterranean climate on a granitic terrain and determined that biotite content was the main factor controlling weathering rates. Le-Pera and Sorriso-Valvo (2000) documented a mean weathering depth of 15 m but suggested that weathering could have reached 50 m or more.

Within the La Posta pluton, the overburden consists of relatively thin colluvium, accumulations of alluvium, and saprolitic material of variable thickness. Fortin (2000) detailed the chemistry and petrology of a La Posta series soil within the Mediterranean hot summer climate. She documented a weathering profile that had not been subjected to intense chemical weathering but had nevertheless lost through dissolution significant amounts of plagioclase. Working in the same microclimate, Mitchell (2000) described the chemistry of a mollisol developed on older La Posta series soils.
Figure 1. The La Post pluton and San Diego County with major roads and highways.
Figure 2. Microclimates of San Diego County
There has been no attempt to link the depth of weathering to micro-climatic zonations. Dahlgren et al. (1997) described only soils along an elevational transect of the Sierra Nevada, California, and concluded that maximum soil weathering (based on cation saturation) occurred at medial elevations but did not carry interpretations into the substrate (saprolites and weathering front). Radzevicus and Pavlis (1999) quantified the depth of weathering in a single location. Using seismic reflection, Radzevicus and Pavlis (1999) interpreted shallow reflections at −60 m as the limits of weathering but did not include correlations to climate. In this thesis, I address the question: Does a correlation exist between the depths of weathering and microclimatic conditions? Seismic data from representative sites are used to address this question.

Seismic refraction surveys were conducted in areas of similar topography and rock type located in different micro-climatic zones.

An attempt was made to use a Schmidt hammer (Type-N) on bedrock outcrops to constrain mechanical rock parameters and assist in seismic interpretation. It was determined that stringent testing procedures should be followed in order to generate reproducible results. Schmidt hammer testing was found to be highly variable and more testing was deemed necessary.
CHAPTER II

GEOLOGY OF THE LA POSTA PLUTON

The 94 Ma La Posta pluton covers an area of 1400 km² (Figure 3). Located 65 km east of San Diego, California, it is the largest of a series of concentrically zoned plutons within the eastern Peninsula Ranges batholith. The La Posta pluton is zoned from a sphene-hornblende-biotite tonalite rim inward to a core of muscovite-biotite granodiorite, and is the product of a single magmatic pulse that crystallized inward (Clinkenbeard and Walewender, 1989). Internal contacts are gradational over distances of several tens to hundreds of meters. Working inwards five lithologically distinct facies exist; they are the border, hornblende-biotite (H-B), large-biotite (L-B), small-biotite (S-B), and muscovite-biotite (M-B) facies (Table 1). Work during this study was conducted in the hornblende-biotite, large-biotite, and small-biotite facies (Figure 4). The La Posta pluton is largely undeformed and possesses euhedral mafic minerals (Clinkenbeard and Walewender, 1989).

Table 1. Average modes of rocks in the La Posta Pluton (Clinkenbeard and Walewender, 1989).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Western</th>
<th>Central</th>
<th>Eastern</th>
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<tbody>
<tr>
<td>Quartz</td>
<td>HB</td>
<td>LB</td>
<td>SB</td>
</tr>
<tr>
<td></td>
<td>25.1</td>
<td>29.4</td>
<td>31.5</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>55.1</td>
<td>54.4</td>
<td>48.6</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>2.7</td>
<td>4.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Biotite</td>
<td>12.7</td>
<td>8.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Hornblende</td>
<td>2.7</td>
<td>1.9</td>
<td>tr</td>
</tr>
<tr>
<td>Muscovite</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td># of modes</td>
<td>3</td>
<td>2</td>
<td>5</td>
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The hornblende-biotite facies is the main outer unit of the La Posta pluton and exhibits some foliation parallel to the pluton margins but is largely massive. This facies is predominantly a sphene-hornblende biotite tonalite and is progressively more enriched in alkali feldspar and depleted in hornblende inward. Hornblende, biotite, and sphene exhibit euhedral crystals up to 7 mm in length.
Rock Description
- Hornblende Biotite
- Large Biotite
- Small Biotite
- Muscovite Biotite
- Mesozoic Metasedimentary Rocks
- Younger Granitic Intrusives

Microclimate Description
- Csb Mediterranean Cool Summer
- Csa Mediterranean Hot Summer
- Bsh Semi-Arid Hot
- Bwh Arid

Figure 3. The La Posta pluton and Transecting Microclimates
Plagioclase crystals (up to 10 mm in length) are subhedral to euhedral. Mafic inclusions are ilmenite, apatite, zircon, and allanite. Quartz exists as discrete or composite grains (Clinkenbeard and Walewender, 1989).

The predominant rock types of the large-biotite facies are sphen-hornblende-biotite and sphen-biotite-granodiorites. Large (5-10 mm) pseudohexagonal books of biotite are present and give the large-biotite facies a “salt and pepper” appearance. There are no large euhedral hornblende crystals like those in the hornblende-biotite facies. However small (1-3 mm) subhedral hornblende crystals are present in the outer portion of the facies and decrease in abundance toward the inward part of this facies. Here hornblende and biotite are otherwise similar in character to that in the outer hornblende-biotite facies. Plagioclase occurs as subhedral crystals (3-4 mm) as large as 10 mm. Alkali feldspar is more abundant and sometimes forms oikocrysts up to 3 cm in size. Quartz is coarser in this facies but is otherwise similar to quartz of the hornblende-biotite facies (Walawender et al., 1990).

Biotite granodiorite of the small-biotite facies is characterized by small (1-4 mm) euhedral to subhedral biotite crystals. Hornblende is scarce while subhedral (1-3 mm) plagioclase crystals are common. Alkali feldspar oikocrysts up to several centimeters in size are also characteristic of the small biotite facies (Clinkenbeard and Walewender, 1989).

Plagioclase feldspar is the most abundant mineral in the La Posta pluton, and is present in all facies, whereas alkali feldspar is typically found only in the three interior facies (as interstitial fillings or poikiolitic patches). Plagioclase compositions vary across the pluton whereas alkali feldspar compositions are relatively constant across the three inner facies.

A metasedimentary screen composed of Mesozoic pelitic schists, magmatic gneisses, and lesser volumes of marble, quartzite, and amphibolite (Clinkenbeard and Walewender, 1989) trends NS over the central portion of the pluton dividing it into western and eastern geographic regions. Two monzogranitic plutons in the central part of the La Posta pluton (Figure 3) probably represent younger intrusive events (Walewender et al., 1990).

Drainage patterns within the western portion of the pluton are joint controlled and trellis-like with short (~1.5 - ~3.5 km) EW tributaries and long (~3.5-8km) NS trunk channels. NS trending segments of the trellis system commonly occur entirely within one of the four La Posta facies (Girty, 2000), and contain first cycle La Posta derived alluvium that
is overlain by a layer of Mottsville series mollisols (entic ultic haploxerolls) (Bowman 1973). The trellis system is not evident in the eastern area of the pluton where vegetation is sparse. La Posta series soils are generally not present on the eastern side of the pluton, hence fieldwork of this study was conducted on the western side (Figure 4).
Figure 4. Field Area
CHAPTER III

SAPROLITE EVOLUTION IN SOUTHERN CALIFORNIA
AND NORTHERN BAJA CALIFORNIA, MEXICO

During latest Cretaceous and early Eocene time the southern California and northern Baja California coastal margin existed as basement rocks and a narrow coastal plain of sedimentary rocks. During this period, basement rocks underwent several hundred to thousands of meters of uplift to the east. An erosion surface of low to moderate relief was developed across the coastal plain. Subaerial weathering ceased with the deposition of Eocene sediments on deeply weathered surfaces. The pre-Eocene weathering surface is thickest where overlain by Eocene sediments. Away from sedimentary cover, modern erosion has worn away the saprolitic material leaving hills covered with spheroidal boulders (Peterson and Abbott, 1974).

In the San Diego region, paleosols developed atop the saprolite were largely eroded prior to deposition of the mid-Eocene Poway and La Jolla subgroups. South of Tijuana, a thick (30 m) laterite paleosol resides atop Late Cretaceous granodiorite. The paleosol is overlain by Eocene sediments of the Delicias Formation (Peterson and Abbott, 1974).

The Tijuana paleosol is defined as a laterite because of the following characteristics; an almost complete decomposition of parent material, the near absence of soluble salts, abundant aluminum oxides, low iron and silica, and an abundance of kaolinite clays. Lateritic soils develop in humid tropical regions and involve deep weathering (Peterson and Abbott, 1974).

Mid-Eocene formations in this region are only slightly weathered in comparison to pre-Eocene sediments and batholithic rocks. Soils developed under today’s arid conditions would belong to the pedocal family, characterized by abundant soluble alkaline and alkaline earth salts and abundant montmorillonite clays. Most soils in San Diego and northern Baja California developed under a more humid and cooler Pleistocene climate and differ slightly from that predicted by today’s climate (Peterson and Abbott, 1974).
The Late Cretaceous to early Eocene weathering surface developed on Cretaceous rocks in the San Diego and northern Baja California region evolved under unique climatic conditions, unlike any in San Diego or northern Baja California since early Eocene time. Most lateritic soils develop in humid arid climates and occur within 25° of the equator. The present latitude (32° N) and climate (Mediterranean hot summer to arid) of the La Posta pluton does not present conditions conducive to the production of laterites (Peterson and Abbott, 1974) and indicates a major change in climatic conditions since early Eocene time.
CHAPTER IV

LA POSTA SOIL SERIES

A mantle of loamy coarse sandy soil has developed on approximately 90% of the western part of the La Posta pluton (Figure 5). The mantle of soil is composed mostly of mollisols (group haploxerolls: subgroups entic and typic haploxerolls) that have developed within both humid and arid microclimates (Bowman, 1973).

La Posta soils are the result of in-place weathering (Fortin, 2000, Girty, 2000, Mitchell, 2000). La Posta series soils are defined as excessively drained loamy coarse sands that formed in materials weathered from granodiorite of the La Posta pluton. The high sand content of La Posta soils, in comparison to tonalite and granite soils, is due to resistance to weathering and high orthoclase content. Plagioclase weathers faster than orthoclase within this environment (Fortin, 2000 and Mitchell, 2000). La Posta soils are on mountain uplands at elevations from 600 to 1400 meters with 5-50% slopes. Mean annual precipitation, rain and winter inter-storm snowmelt, is between 38 and 51 cm, while mean temperature is 13.3-14.4 °C. These soils are frost-free 170-190 days annually (Bowman, 1973).

In a representative profile of a La Posta series soil, the surface loamy coarse sand layer is grayish-brown and brown, slightly acid to neutral and about 20.5 cm thick. The layer below 20.5 cm is brown, slightly acid loamy coarse sand that grades to deeply weathered granodiorite at about 74 cm (Bowman, 1973).

Bowman (1973) defined a soil profile as the sequence of natural layers, or horizons, extending from the surface down into the parent material. A soil profile within the study area typically possesses the A, C, and R horizons. Horizon “A” is the surface layer, “C” the saprolite, and “R” the bedrock. The A horizon supports plants, C is friable moderately weathered granite, and R is unweathered granodiorite bedrock. In the C-horizon root intrusion diminishes with depth and joints and cracks are rounded by weathering processes. In R cracks are sharp and angular.

Fortin (2000) described a soil profile (Figure 6) in the large biotite facies within the Mediterranean hot summer microclimate zone. During this work Fortin’s profile was used as
Figure 5. Significant Soils and Lines # 4 & 9
LaE2 La Posta loamy coarse sand 5-30% slopes eroded
LaE3 La Posta loamy coarse sand 5-30% slopes severely eroded
LcE La Posta rocky loamy coarse sand 5-30% slopes
LcE2 La Posta rocky loamy coarse sand 5-30% slopes eroded
LcF2 La Posta rocky loamy coarse sand 30-50% slopes eroded
MvC Mottsville mollisol
Figure 6. Soil Pit at Line #7. Dashed red line is base of A horizon (-30.5 cm). Blue dashed line shows recent rainfall percolation. LaE2 indicates La Posta loamy coarse sands as they appear at the surface.
a standard for comparison purposes. At the surface, a well developed A horizon (50.8 cm) resides above C. This brown, loamy sand is characteristic of La Posta soils. Below A, a 2.5-3 m thick C horizon exists. A lack of cohesion, and a generally friable nature characterize the weathered rock in C. Cohesion decreases upward from poor/moderately poor at the base to cohesionless at the top of C. Gravel sized pieces of weathered granodiorite are present at the base of C and become smaller towards the top. Plant roots intrude into the upper 1-1.5 m of C. Bedrock was classified as horizon R and was characterized by hardrock features and sharp angular edges. Fortin (2000) did not describe the characteristics of R much below its contact with C.

As determined by mineral depletion ratios, the soil profile studied by Fortin (2000) had not been subjected to intense chemical weathering, an observation that may imply immature development of the studied profile. However partial dissolution of plagioclase and K-feldspar was documented by Fortin (2000). Plagioclase appears to have weathered at a faster rate than K-feldspar (Fortin, 2000; Scholten, 1997). During the development of the A ~6 grams/100 grams of rock were removed (Fortin, 2000). The work of Fortin (2000) was extended and strengthened by Mitchell (2000).

Vegetation (Figure 7) supported by the La Posta soil series includes chamise (Adenostoma fasciculatum), deanothus (Ceanothus spp.), sumac (Rhus spp.), scrub oak (Quercus dumosa), red shank (Asenostoma sparsifolium), California live oak (Quercus agrifolia), sagebrush (Artemisia spp.), and annual grasses (Mitchell, 2000).
Figure 7. Photo of Vegetation Within the La Posta pluton. Scrub Oak (green) at middle right and sagebrush. View to the north along La Post Rd. Interstate 8 overpass is below Mount Laguna. Dashed line marks the approximate northwestern boundary of pluton.
CHAPTER V

MICROCLIMATE CLASSIFICATION OF STUDY AREA

San Diego County includes two major climatic zones (Dry, B and Warm rainy climates, C) that are further subdivided into five microclimates of which four exist within the terrain underlain by the La Posta pluton (Eidemiller and Finch, 1972).

Semi-arid climates (Bs), are those in which total annual evaporation exceeds precipitation. Within the semi-arid cool (Bsk) microclimate, average annual temperature is under 18 °C. For the semi-arid hot (Bsh), the average annual temperature is above 18 °C.

Mediterranean climates (Cs) have at least three times as much precipitation in their wettest months as their driest months. In Mediterranean hot summer (Csa) climates the average temperature during the hottest month is above 22 °C, whereas in Mediterranean cool summer (Csb) climates the average for the hottest month is below 22 °C.

Mediterranean cool summer, Mediterranean hot summer, semi-arid hot, and arid microclimatic belts transect the La Posta pluton and could influence rock and soil horizon development patterns (Figure 3). The hornblende-biotite facies is exposed in the Mediterranean hot summer and arid environments while the large and small-biotite facies crop out in the Mediterranean hot summer, semi-arid, and arid climactic zones (Girty, 2000).
CHAPTER VI

GROUNDWATER IN THE STUDY AREA

The influence of groundwater within the La Posta pluton is clear. Abundant groundwater will accelerate the weathering of granite provided soluble minerals are adequately removed during weathering.

Saprolites are an important groundwater reservoir, due to their thickness and high pore volume (Schloten, 1997). Water table levels are marked by a general decline that is due to reduced precipitation and increased domestic usage as evidenced by springs in the Mount Laguna area. Excessive pumping at one location lead to a drop from 120 to 140 m in the years 1958 to 1968 (Lower, 1977). Wells drilled in the crystalline rock in the Mount Laguna area can expect to intercept the water table at about 15 m. Two deep wells in Mount Laguna demonstrate “cascading water”. A well drilled to 305 m at the north end of Laguna Meadow intercepted the normally saturated zone (shallow) but also intercepted a zone of saturated fractures at about 275 m. Between the two zones an intermediate zone existed with low hydrostatic head. Thoroughgoing fractures that connect these two zones provide an avenue for groundwater movement from the upper zone to the lower zone. A well drilled between the two will act as a through-going fracture and will rapidly deplete the upper zone. The same phenomenon was encountered on the east side of the meadow in another well.

The upper saturated zone involves groundwater circulating through alluvium, weathered mantle (saprolite), and fractured bedrock. The base of this zone is 90-120 m in depth. The depth to the lower zone is variable 180-275 m. In the lower zone, groundwater exists in major thoroughgoing fractures that transect the upper zone continuing downward to a point where the fractures are sufficiently tight to preclude the circulation of groundwater. The fractures between the two zones are not matured. Periods of increased precipitation may raise the level of the lower zone (Lower, 1977).

Infiltration in residuum in meadowed areas (Motsville Soils) may be low (0.03 -0.46 cm/min), but with increased rates can occur along meadow perimeters. Infiltration rates in
chaparral covered slopes range from 0.66 to 0.76 cm/min. The highest infiltration rates are in stream channel coarse-grained materials (Lower, 1977).

Percolation is the movement of groundwater downward under gravity between soil and the saturated zone. Percolation will through voids left by mineral decomposition and expansion. Seasonal saturation is likely to occur. Evapotranspiration is highest in areas of highest temperatures.

Groundwater production is low, as indicated by yields from wells of the Campo, Manzanita, and La Posta Reservations of less than 40 gal/min (Moyle and Downing, 1978). The abundance of groundwater in crystalline rocks depends on the degree of weathering, fracture and joint patterns, and rock type. Rocks in San Diego display a well-developed joint pattern that enhances the rate and degree of weathering. In highland areas, residuum lies above the water table. The following rock types produce successively decreasing yields: tonalite, metamorphic rocks, gabbro, and granodiorite (California Department of Water Resources, 1967).

The saturated hydraulic conductivity of saprolites is about two times higher than overlying soils. Saprolites show a decreasing pore volume and water capacity with depth. Pore volume in the soil is only slightly different than underlying saprolite due to alignment of clay particles produced during shrinking and swelling. Greatest hydraulic conductivity reaches a maximum in the middle saprolite zone along with the highest amount of macro pores (Scholten, 1997).

The depth to groundwater in wells is regularly monitored by the County of San Diego (Figure 8). Seasonal and annual fluctuation due to production and weather is expected. Depth to groundwater in some area wells has been monitored for the past nine years. The average (over time of monitoring) depth to groundwater is presented in Table-2. Many of the wells with water close to the surface are located in alluvial areas or involve limited production and drawdown. The deeper groundwater elevations may occur as a result of regular production and drawdown or local site characteristics such as topography.
Figure 8. Location of Groundwater Wells, Seismic Lines, and Schmidt Hammer Sites
Table 2. Depth to Groundwater in Wells

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Mean Depth to Water, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quail Rd.</td>
<td>-16.9</td>
</tr>
<tr>
<td>Radioactive</td>
<td>-33</td>
</tr>
<tr>
<td>Oak Drive</td>
<td>-6.7</td>
</tr>
<tr>
<td>Lupine Water District</td>
<td>-38.9</td>
</tr>
<tr>
<td>Park (abandoned)</td>
<td>-7.6</td>
</tr>
<tr>
<td>Hubbard Domestic</td>
<td>-30.2</td>
</tr>
<tr>
<td>Morning Star Handug</td>
<td>-6</td>
</tr>
<tr>
<td>Morning Star Playhouse</td>
<td>-4.2</td>
</tr>
<tr>
<td>UTZ</td>
<td>-2.1</td>
</tr>
<tr>
<td>Albam</td>
<td>-1.6</td>
</tr>
</tbody>
</table>
CHAPTER VII

HYDROLOGIC AND STRUCTURAL CONSIDERATIONS

This study seeks to delimit the vertical depth-dependent extent of weathering in the La Posta pluton. Weathering is defined as the alteration and or breakdown of rocks in situ and in the range of temperatures characteristic of the earth’s surface (Figure 9). The weathering style of granite is determined by its low permeability and the relative stability of characteristic mineral assemblages (Radzevicus and Pavlis, 1999).

Physical Parameters of Weathering

The downward limits of weathering are defined as the weathering front, which generally mimics topography, but is deepened along valleys and thinned at ridgelines (Twidale, 1982). Granite weathering is focused along fractures acting as conduits for chemical weathering (Radzevicius and Pavlis, 1999). Irregularities (protuberances) on the weathering front occur where resistant corestones occur (Twidale, 1982). Working in granitic terrain of similar climate, Le Pera and Sorriso-Valvo (2000) determined a mean weathering front at 15 m of depth but indicated that maximum weathering could extend 50-60 m or more.

The porosity and permeability of La Posta granodiorite is highest at the surface where fracture and joint sets allow the intrusion of water and humic acid. Typical unweathered granites have porosities of 0.1-1.2% and almost no permeability (Twidale, 1982).

Sheet jointing can be observed on bedrock exposures of the La Posta pluton. Workers have observed sheet structure with horizontal slabs as thick as 10 m and to depths of 100 m deep in quarries (Twidale, 1982). Others (Green and Mair 1983) have interpreted “major subhorizontal fractures” up to 800 m within batholithic terranes. The thickness of slabs of rock between individual sheet joints usually increases with depth. Sheet jointing commonly runs parallel to the land surface. In the vicinity of steeply dipping faults, sheet joints dip steeply also. Sheet joints cut across structure in bedrock and postdate the consolidation of the rock. Weathering may be focused along sheeting joints, as they are natural pathways for water (Radzevicus and Pavlis, 1999).
Figure 9. Weathering exposed on a roadcut at La Posta Rd and Old Highway 80. Vertical and dipping fractures have facilitated localized weathering. Spheriodal boulders close to the top grade into angular blocks (with possible translocation) and then to intact granite with weathering along fractures.
Some resistance to weathering is via case hardening, a process resulting in the formation of oxides at the surface of exposed rocks (Twidale, 1982) such effects were observed on boulders in the eastern part of the La Posta pluton.

**Erosion and Surface Morphology**

Surface morphology is a reflection of climate and therefore plant cover while the magnitude of rainfall events will determine the character of subsurface weathering. Runoff and erosion is lowest in vegetated areas primarily because leaves and branches dissipate rainfall energy by breaking up droplets and enhancing infiltration. Scholten (1997) determined that surface soils (higher clay content) possess greater shear strength than saprolite, which has a shear strength less than unconsolidated sands and silts. Saprolites possess increased shear strength with depth, a characteristic that probably reflects decreasing weathering intensity (ibid). The loss of soil cover above the saprolites will lead to quickened erosion and gully development.

Erosion is limited by the frequency and magnitude of events, not the availability of weathered material (Canton et al., 2001). The majority of sediment is transported only by a few high rainfall events annually, generally those above the runoff threshold. Most runoff is generated on bare and lichen covered soil surfaces, i.e., those with the highest erosion coefficients. Cooler climates incur more high rainfall events and are prone to high magnitude erosion events (Canton et al., 2001). Sediments may be temporarily trapped in channels and rills in between high rainfall events. These sediments are flushed out during high rainfall events and rills and channels are deepened.

Infiltration rate will greatly affect the rate of chemical weathering. Infiltration is lowest in areas of sheet erosion and highest in well vegetated areas. Some soils “crust” as an initial reaction to rainfall and this quickens the time to runoff. Soil crusts reduce the hydraulic conductivity of soil.

The available water capacity of saprolites in the form of plant available water in pores of 50 to 0.2 μm in diameter was two to four times higher than in overlying soils (Scholten, 1997). Conditions for re-vegetation are greatest where saprolites form a major portion of the rooting zone and control the available water capacity. Continually wet conditions are the most conducive to grus formation (Dahlgren et al., 1997).
Chemical Weathering of Bedrock and Saprolite

The effectiveness of chemical weathering is controlled by the permeability (meteoric water penetration rate) of the saprolite, solubility of the included minerals, and rate at which soluble minerals are flushed from the system. Low permeability produces prolonged pore water contact with minerals and allows thorough mineral dissolution but terminates at a saturation point. The advance of weathering is assumed to equal the rate of penetration (primary hydraulic conductivities) of meteoric waters into pristine granite (White et al., 2000). Permeability in bedrock is primarily intragranular and is created by internal weathering of networks of interconnected plagioclase crystals (ibid). The separation of weathered and fresh rock may be a distinct sharp contact as chemical reactions are grain by grain (Radzevicius and Pavlis, 1999).

In granitic soils, water reacts with feldspars to produce clays and may involve hydrolysis, which provides for the dissociation of water and the release of hydrogen ions. Weathering of granite produces neutral or faintly acid conditions with pH 4-6 (Twidale, 1982). Quartz-rich rocks are more susceptible to attack by alkaline waters than to slightly acidic waters. Most groundwaters contain enough SiO₂ to be fully saturated with respect to quartz but rarely with plagioclase while those with pH < 7 are commonly saturated with K-feldspar (Girty, 2000).

Slight hydration of biotite and other minerals is enough to bring about disaggregation of granite and the formation of saprolite (Isherwood and Street, 1976). Water enters crystal lattices of biotite and expands (Dahlgren et al., 1997, Isherwood and Street, 1976, Le Pera and Sorriso-Valvo, 2000, Radzevicius and Pavlis, 1999, and Twidale, 1982). The formation of microfractures and expansion of biotite can reduce the bulk density of original rock by 25% during the formation of grus (Isherwood and Street, 1976). Fractures in biotite extend as micro fractures into quartz and feldspars. The biotite is then altered to vermiculite, chlorite, and kaolinite depending on circumstances. Boulder preservation may be due to low biotite content (Le Pera and Sorriso-Valvo, 2000). Clay films developed on feldspar fractures can also cause the dissaggregation of granite (Twidale, 1982).

Mineral alteration has been found to change with depth. White et al. (2000) determined differential rates of feldspar weathering in granite regoliths and a soil saprolite complex (in Atlanta, GA, elevation 230 m, 163 cm/yr rainfall, average temp 20.6 °C).
Plagioclase was found to be converted to kaolinite at depths > 6 m in the granitic bedrock, whereas K-feldspar remained pristine in the bedrock subsequently weathering to kaolinite in the overlying saprolite. At High Vista, California, Radzevicius and Pavlis (1999) encountered an abrupt decrease in drilling rates and degree of alteration of biotite and chlorite to smectite clays at depths of 70-80 m. Montmorillonite is expected as an end product of the weathering of feldspars in an arid mid-latitude climate (Twidale, 1982, Peterson and Abbott, 1974).

**Soil Profile Development**

Clastic sediments generally are not produced directly from bedrock and instead represent material derived from weathering profiles (Fortin, 2000, Girty, 2000, and Mitchell, 2000). The degree of alteration endured by La Posta soil materials (rock and mineral fragments) is a function of parental rock type (facies), texture, and relief. Texture and relief are largely controlled by climate (precipitation and temperature) which itself determines the presence or absence of plant cover (Girty, 2000).

**The Influence of Vegetation on Rock Weathering**

Moulton and Berner (1998) resolved the influence of plant assisted weathering in basaltic bedrock by comparing the amount of Ca and Mg in streams in vegetated and non-vegetated terrains. The rate of release of Ca and Mg to streams and vegetation was two to five times faster in vegetated areas than in barren areas. Vegetation absorbs dissolved silicon released from the weathering of granite. Otherwise silicon is available for mineral formation or is flushed from the profile towards adjacent drainages (Alexandre et al., 1997). The absorption of silicon by plants increases the chemical weathering rate without accelerating denudation (ibid). The precipitation of silica at the base of a soil profile indicates oversaturation and therefore no dissolution below this depth (Alexandre et al., 1997).
CHAPTER VIII

TRANSPORT- AND WEATHERING-LIMITED DENUDATION

The character thickness of the mantle of La Posta soil series is determined by the ratio of the rate of production of weathered materials (weathering and mass wasting) versus the rate of transport (removal via erosion) of weathered products. When erosional processes can transport more material away than is delivered by weathering, the system is said to be weathering-limited. In contrast, in a transport-limited system the rate of delivery of material by weathering and mass wasting is at least as great as the rate at which material is removed by erosion. Weathering-limited denudation more commonly occurs at the divide and upper part of a slope because denudative debris increases in accumulation down slope. The lower boundary of weathering-limited denudation lies at the transition between bedrock and regolith covered slope (Ahnert, 1996).

Weathering-limited slopes are underlain by bedrock. The morphology of such slopes is determined by the weathering that occurs locally, e.g. sheet jointing and vertical fractures giving rise to block disintegration. Transport-limited slopes are covered by a mantle of soils and develop in dynamic equilibrium between processes involved in weathering, mass wasting, and erosion (Ahnert, 1996).
CHAPTER IX

THE SEISMIC REFRACTION METHOD

The seismic refraction method was employed to determine subsurface inhomogenities of the La Posta pluton. The refraction method consists of measuring (at discrete ground surface locations) the arrival times of compressional waves generated by an impulsive energy source (Figure 10). Seismic energy will propagate through subsurface layers in the same manner that light rays propagate through transparent media. When a light ray (seismic ray) travels across the interface between media with unequal transmission velocities it will incur an angular deviation (refraction) in relative travel, which is dependent on the ratio of transmission velocities.

Delineation of the Subsurface by Seismic Refraction

Snell’s Law describes the refraction of light rays and is fundamental to the interpretation of seismic energy in subsurface layers (Figure 11).

\[
\frac{\sin \alpha}{\sin \beta} = \frac{V_1}{V_2}
\]

A compressional wave generated at the surface will propagate downwards and outwards (Huygens’ principle). As the energy propagates downward across an interface, almost all the compressional energy is transmitted (refracted) into the medium with higher velocity until the angle of incidence (\(\alpha\)) equals the critical angle: (which occurs when \(\beta = 0\)).

\[
\sin \alpha = \frac{V_1}{V_2}
\]

The critical angle is unique to the ratio of transmission velocities. Past the angle of critical incidence almost all energy is reflected into the low velocity medium (upper). An incident ray arriving at the angle of critical incidence will be refracted to travel along the interface at the higher of the two velocities. As the critically refracted ray travels along the interface, it continually generates seismic waves (head waves) in the lower velocity (upper) layer. These depart form the interface at the angle of critical incidence. The arrival of the head waves is detected as vertical acceleration (by the geophones) and represents only a portion of the initial energy (Sjogren, 1984).
Figure 10. Seismic Refraction Survey, after Sjogren (1984).

Figure 11. Snell’s Law
Seismic refraction surveys resolve data in two dimensions and herein will be described as such. The shear component of seismic waves and the proportion of compressional energy transformed into such waves at layer boundaries is not recorded by common refraction equipment and can be ignored. Refraction equations assume that each layer within a stratigraphic sequence is isotropic with regard to its propagation velocity. The ray paths used to depict seismic energy are made up of straight-line segments representing seismic energy emanating from a point source to a point on the surface of a propagating sphere.

The procedure involved in generating a seismic record involves three steps: generation of seismic energy, detection and recording of seismic energy, and calculation/interpretation of the data. To generate an impulsive seismic source, a sledge hammer is struck against an aluminum plate (placed at ground level). The acoustic energy produced by striking the plate (also known as a shot) displaces media (soil/rock) as a spherically expanding compressional wave. A trigger switch (activated by the hammer blow) will signal the seismograph to begin recording (Time, T=0). Geophones (vertical accelerometers) are placed in a line at regular intervals along the ground surface away from the shot point, and continually record for a predetermined elapsed time period (from T = 0 to any user defined time, 250-500 ms for this study). The datum recorded by the seismograph is a collection of individual seismograms (for each geophone) known as a shot gather (Figure 12). Arrivals of the compressional wave are visible on the seismogram (large positive or negative inflections on seismic trace). The arrivals can be arbitrarily or automatically (by seismograph) picked and are recorded as elapsed time. The arrival times (Figure 13) are plotted as time after the shot (delay) versus distance from the shot (geophone offset).

The first few arrivals (geophones closest to the shot) will plot as a straight line starting at the origin. The slope of this line is the reciprocal of the velocity of the upper layer (1/V₁). At some distance, the critical distance (Xₖ), the slope of the line connecting the points along the time distance plot is observed to change. The reciprocal of the slope of the second line segment (1/V₂) is the velocity of the second layer. Projecting the V₂ line segment to the time axis yields the intercept time (Tᵢᵢ). Intercept time (Tᵢᵢ), layer one velocity (V₁), and layer two velocity (V₂) are then used to calculate the thickness of layer one (Z₁):
Figure 12. Shot gather from Line 1, Shot #2 as seen in Sismpointer Module. Numbers along top are stations (geophones). Wiggle trace seismograms are filled on positive inflections. Blue lines are first break picks. Seismograms are shown with 100% visual gain (user defined to 999%). Module automatically chooses first break picks, which can be revised by user. Film (file) number appears in upper left. Time and trace number of pointer (red bar) appear at lower left. User may zoom in on individual traces for accurate first break picks.
Figure 13. Time Distance Curve (top) and Refracted Raypaths (lower).
\[ Z_1 = \frac{T_{i2}V_1}{2\cos(\sin^{-1} \frac{v_1}{v_2})} \]

\[ Z_1 = \frac{T_{i2}V_1V_2}{2\sqrt{V_2^2 - V_1^2}} \]

Consequently the thickness for layers 2 \((Z_2)\) and 3 \((Z_3)\) can also be calculated:

\[ Z_2 = \frac{\left[ T_{i3} - T_{i2} \frac{\cos(\sin^{-1} \frac{V_1}{V_3})}{\cos(\sin^{-1} \frac{V_1}{V_2})} \right] V_2}{2\cos(\sin^{-1} \frac{V_2}{V_3})} \]

\[ Z_3 = \frac{\left[ T_{i4} - T_{i2} \frac{\cos(\sin^{-1} \frac{V_1}{V_4})}{\cos(\sin^{-1} \frac{V_1}{V_2})} - 2Z_2 \cos(\sin^{-1} \frac{V_2}{V_4}) \right] V_2}{2\cos(\sin^{-1} \frac{V_3}{V_4})} \]

*for the derivation of these equations see Redpath (1973).

Weathered material (saprolite) commonly has seismic velocities an order of magnitude smaller than the unweathered parent material (Radzevicius and Pavlis, 1999). All depths calculated using the refraction method are measured normal to the interface. 2D crosssections of velocity changes were produced using depths calculated using refraction analysis (Figure 14).

**The Propagation of Seismic Energy**

The propagation and speed of seismic waves depends on elastic properties and the density of the medium of travel. Stress \((S)\) applied to a body (such as a seismic source) will alter the size and shape of the body. External stress gives rise to resisting forces within the medium. Hooke’s Law states that strain (prior to the elastic limit) is proportional to stress. Opposing forces (dependent on material) will act to resist such distortions. The ability to resist deformation and the tendency of a body to restore itself to its original shape and volume define the elasticity of the material.

When stresses and strains are not in equilibrium (applied stress is removed), built up strain energy is removed through propagation of an elastic wave. Huygens’ principle states that seismic energy propagates outward in a hemispherical fashion.
Figure 14. Depth Interpretation of Seismic Refraction line #1.
A compressional wave traveling through a medium produces alternating contractions and dilatations. Refraction exclusively uses longitudinal ($V_p$) velocities as they are first to reach geophones and will obscure later arrivals (see equation #7).

\[ V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{k + (4/3)\mu}{\rho}} = \sqrt{\frac{E}{\rho (1+\sigma)(1-2\sigma)}} \]

Wavelength ($\lambda$): $\lambda = V T$

\[ \lambda = V/f \]

Period (T) \hspace{1cm} T = 1/f

Frequency (f) \hspace{1cm} f = 1/T

Density ($\sigma$)

Lame's Constants ($\lambda, \mu$)

Bulk Modulus (k)

Young's Modulus (E)

Surface waves have little application to refraction work because of shallow penetration. Surveys may encounter velocities in dry unconsolidated sediments lower than that in air. Seismic velocity in water is 1450-1500 m/s, but with saturated materials and a high organic content, seismic velocities can be lower. In anisotropic media the velocities are higher when measured along strike rather than perpendicular to it (Redpath, 1973).

**Seismic Refraction and Groundwater**

Conditions found on the La Posta pluton are favorable for the detection of the groundwater surface using seismic refraction. Dry loose unconsolidated sands found at the surface yield seismic velocities averaging 885 m/s (results of this study). With saturation, these sediments should yield seismic velocities of 1600-1800 m/s. Similar velocities are expected in granitic saprolites represents varying degrees of weathering. When results of a refraction analysis indicate the likely detection of the groundwater surface, on site confirmation (nearby wells or the observation of springs and/or phreatophytes) is prudent.

**Problems and Pitfalls**

**Velocity Reversal**

In most cases seismic velocity increases with depth. However a low velocity zone (LVZ) may underlie a zone of higher velocity. For example, a buried paleosol could yield a
low velocity zone. The low velocity zone will impart greater (than actual) depths to refractive layers. Seismic rays are bent downwards as they cross into low velocity zones (the rays will again bend upwards as they cross into a higher velocity zone). The refraction analysis cannot directly detect the low velocity zone, it may be confirmed by drilling. During thickness calculations a low velocity zone is undetected and is added to the overlying layer. To correct for velocity reversals, an up-hole (shots in a wellbore) velocity survey may be necessary. Velocity reversals rarely occur in shallow surveys, and are rare in granitic terrains. I can not discount the possible occurrence of velocity reversals within the study area.

**Blind Zone**

This phenomenon can occur in surveys with three or more layers. To render classic travel time curves (straight line segments with discernable breaks in slope) there must be either marked changes in velocity between layers or adequate thicknesses of layers. A “blind zone” occurs when an intermediate layer is either to thin or does not represent a marked increase in velocity from the overlying layer and the underlying layer has a relatively high velocity. The resulting travel time curve will yield velocities for only the upper and lower zones because the refractions from the bottom of the intermediate layer will arrive prior to those coming form the top of the intermediate layer. Straight-forward interpretation of the time distance plots will yield over-estimation of the thicknesses for the upper layer. It may be necessary to generate a shot at depth or drill to determine the presence and thickness of a blind zone. Vertical Seismic Profiling (VSP) acts to confirm/deny interpreted refractions/reflections (Fletcher et al., 1990, Sheriff and Geldart, 1995). Computational methods have been developed to determine the thickness/presence of a blind zone (Redpath, 1973).

**Gradual Increase in Velocity**

The transition from corestones in the saprolite to locked corestones yields a gradational change in seismic velocities (Radzevicius and Pavlis, 1999, Fletcher et al., 1990). A gradual increase in velocity with depth will yield curved travel time plots without discrete breaks. A curve of this nature can be transformed into a velocity versus depth curve by means of tedious graphical integration (Redpath, 1973). Curves representing gradual
increase in velocity can be thought of as a few straight time versus distance segments, thus allowing thickness and velocity calculations.

**Lateral Changes in Velocity**

Lateral variability may be due to differing degrees of consolidation in sediments. Velocity changes in the soil layer may also be due to changes in grain size and mineralogy. Coarser, more quartz rich, sediments will yield higher velocities. Areas with alluvial and colluvial accumulation should yield lower first layer velocities due to low consolidation and abundant fine grained materials (clays/silts).

**Weathering**

Saprolite and bedrock can produce lateral changes in velocity. Anisotropic differences may be as great as 40% in rocks with finely bedded structures such as sandstones and shales (Redpath, 1973). Differential weathering along joints and fractures will yield lateral velocity changes for a given depth. An irregular weathering front will yield inaccurate arrival times due to the torturous raypaths of refracted seismic energy. Using delay times can correct for irregular weathering surfaces. The weathered top of a rock body may represent a zone of gradual transition into higher velocities. The first arrivals may not come from the top of the rock body but from a point within it. Radzevicius and Pavlis (1999) determined the presence of the weathering front via seismic reflection as a “bright impulsive arrival” with “irregular velocity move out” at nearly constant time and depth on all data. Their interpretations were corroborated by a velocity discontinuity (marked increase) in a borehole velocity survey at that location. The downward and upward propagation of seismic energy is channeled through cores of intact, unaltered portions (boulders) of the weathered granite. Rays traveling through corestones are scattered strongly (Radzevicius and Pavlis, 1999).

**Attenuation**

The seismic source used for this study, a sledge hammer and strike plate, produces a signal of 20-80 Hz (Fletcher et al., 1990). With increasing distance from the shot point, the higher frequency (shorter wavelength) energy is progressively absorbed (attenuated). Due to the signal’s increasing wavelength, the energy may refract from progressively thicker beds (Redpath, 1973). Stacking, i.e. summing seismograms of repeated shots at the same location, will increase the signal to noise ratio.
CHAPTER X

TOOLS AND TESTING CONDITIONS

An attempt was made to run all seismic lines under similar conditions (Figure 4). All lines were run on the surface in areas with La Posta loamy coarse sand, LaE2. La Posta loamy coarse sands represent active in place weathering of the pluton. The weight and amount of equipment limited sites to areas proximal to county and reservation roads. Generally flat lying sites were chosen to limit the influence of topography on the data (Figure 15). Sites were selected in unaltered terrain (no mechanical fills or deep roadcuts). Brush in these areas is not dense and allows for straight lines with regularly spaced geophones. Geophone spacing was either 5 or 6 m (takeouts on geophone cable spaced at 6 m). A standard of 24 geophones per line was used and one line had 36 (maximum allowed by equipment). Shot point spacing was always a factorial of the geophone spacing for simplicity. The maximum shot point offset was 150 m from the nearest geophone. When executing shots at this distance, the signal produced by the sledgehammer was highly attenuated and multiple stacks were necessary (see seismic pitfalls). The number of shot points per line was not consistent. For future lines the author recommends five shots per line, two end offset shots, an end shot at each end, and one midpoint shot. End offset shots allow for better calculation of layer thickness and midpoint shots can indicate any irregularities along the refraction interfaces.

Lines were run in each of the three microclimates: Mediterranean hot summer (Csa), semi-arid hot (Bsh), and arid, (Bwh), to determine to influence of microclimate on the development of soils and saprolites across the La Posta pluton. Eleven lines were run; five in Mediterranean hot summer, three within semi-arid hot, and three in the arid microclimate. This distribution of seismic lines allowed assessment of both the types and rates of change in regolith across the La Posta pluton.
Figure 15. Photo of Seismic line #15. Lying within the semi-arid hot microclimate and small biotite facies. White measuring tape is for geophone spacing. Geophone cable spool at lower right.
CHAPTER XI
DATA PROCESSING

Shot gathers were previewed as time traces in the field on the Strataview (Figure 16) LCD screen. “Test shots” were conducted to determine the functionality of the equipment, such as correct geometry inputs and working geophones. After proper geometry was established (user input on seismograph), data acquisition began. Especially noisy or delayed shot gathers were not saved. At each shot point, it was necessary to stack multiple shots. The seismograph automatically stacked consecutive shots until the user manually saved the stacked seismogram (author did not discover this feature until well into data acquisition).

Note, many of these lines were run by the author without assistance. I recommend at least two people be present when executing seismic refraction lines. In the field, shot gathers were saved in the SEG2 file format.

No bandpass filtering was done. Such filtering is uncommon in refraction studies but may remove ground roll (Radzevicius and Pavlis, 1999). Field stacking of gathers may have accomplished this effect. No deconvolution was applied.

Saved SEG2 shot gathers were imported to and read by the Rockware-Winsism seismic refraction software. Winsism is intended for shallow seismic refraction studies, usually for engineering. The shot gathers were viewed in Simptr, the Winsism first break picking module. Early first breaks were easily determined while using Simptr. Later arrivals (most distant geophones) were harder to determine due to attenuation. While Simptr did offer gain control, the signal at distant geophones had incurred significant attenuation and the relative vertical acceleration due to the seismic signal did not represent as great a differential over ground roll as that incurred at primary geophones. The user-defined first break picks were recorded in time by Winsism. The automatic first break picking option accurately picked only the first and most prominent breaks.

The first break files were then imported into a geometry file. Winsism offered an automatic geometry file generation option or a user defined geometry file. Geometry files of this study were all user defined. With the geometry file complete, Winsism posted arrival
Figure 16. Photo of Seismograph and power source. Geophone cables are inserted at right. Trigger source cable lies to the right.
times as time-distance plots (Figure 13). Using the time distance plots, discrete velocity line segments (of the same slope) were user determined and velocities (inverse of slope) for each layer were calculated. Winsism would calculate the depth of each layer (all but the terminal layer) below each shot point. The user could accept or refute the layer depths, and were saved if acceptable. Winsism offered the option of producing a seismic cross-section showing approximate depth to refractions and velocities at that layer. Possibly a glitch in the software precluded accurate portrayal of the seismic cross-section. Winsism also offered a velocity gridding display, using ray tracing. The velocity gridding is supposed to produce datasets and images displaying lateral velocity changes. This module was not used as a specific shot geometry was required.
CHAPTER XII

THE SCHMIDT HAMMER

The Schmidt Rebound Hammer (Figure 17) was developed to measure the surface hardness of concrete. It can also be used to determine various rock characteristics. In an attempt to constrain the bedrock characteristics, Schmidt hammer (Type-N) data were acquired in four locations proximal to seismic lines of this study (Figure 4).

Operation and Use of the Schmidt Hammer

The mechanics of a Schmidt hammer are simple. A spring-loaded piston (hammer) is positioned vertically over the testing surface. Depressing and holding a button on the side of the hammer releases the piston, flinging it towards the rock (impact energy is 2.207 Nm). As the piston rebounds from the test area, a ratcheting mechanism within the hammer will prevent the piston from falling back down towards the testing surface after it has reached its maximum rebound height. A window on the side of the hammer will yield a rebound value and is used to determine compressive strength (measurable range of 10-70 N/mm²) in concrete. Rebound height varies proportionally with surface hardness and compressive strength. Using a Schmidt hammer on rocks can yield rock properties: Young’s modulus, compressive strength (uniaxial strength), density, Lamé’s constant, and seismic velocity (using Birch’s law).

The Schmidt hammer was used on bedrock outcrops or exhumed corestones of the La Posta pluton to determine bedrock properties in support of seismic interpretations. Level testing areas were chosen and thoroughly cleaned with an electric grinder (using a masonry disc) to clean the surface and remove the outermost weathered area. Five test areas per site were prepared and five rebound readings per site were taken. Test areas were sufficiently spaced to ensure that subsequent tests/hits would impact undamaged rock. Testing near fractures or on small samples was avoided, otherwise hammer rebound (HR) values would be reduced by shaking or previous deformation.
Figure 17. Schmidt hammer in testing position.
Determination of Rock Properties Using the Schmidt Hammer

Katz et al. (2000) determined empirical relationships between Schmidt hammer rebound values and the laboratory measured values of Young’s modulus, uniaxial compressive strength, and density.

\begin{align}
\ln(E) &= -8.967 + 3.091 \times \ln(HR) \pm 0.101 \quad (R^2 = 0.994) \\
\ln(U) &= 0.792 + 0.067 \times (HR) \pm 0.231 \quad (R^2 = 0.964) \\
\rho &= -2874 + 1308 \times \ln(HR) \pm 164.0 \quad (R^2 = 0.913)
\end{align}

HR: Hammer Rebound value  
R: Correlation factor  
E: Young’s modulus (Gpa)  
U: Uniaxial Compressive Strength (Mpa)  
\( \rho \): Density (kg m\(^{-3}\))

The third term in each of the above equations is the standard error for estimation of the relevant variable. For each equation I used rebound values representing the upper 50% of individual impacts. Tests were performed according to the recommended procedure of the International Society for Rock Mechanics.

Good constraints on bedrock (unweathered) velocities were necessary to confirm terminal depths of weathering. Direct measurement (VSP and laboratory studies) of bedrock velocity was difficult. The calculated density was used to derive theoretical bedrock velocities using Birch’s law:

\begin{equation}
V_p = \left( \frac{\rho}{0.31} \right)^{4}
\end{equation}

The author sought to attain “bedrock” velocities during refraction analysis to verify detection of the basal weathering front. Exposed, spheroidal, non-grassified boulders were desired as they were interpreted to most closely represent the unweathered bedrock.

In granite and syenite, Katz et al. (2000) found good correlations between the calculated and laboratory determined Young’s modulus. Good correlations suggest their (ibid.) samples were well cemented and elastic. They cautioned however that correlations would be sensitive to rock type.
The Schmidt hammer has been used to determine the degree of rock weathering at the surface. Le-Pera and Sorriso-Valvo (2000) suggest that accelerated biotite weathering greatly reduces boulder hardness. Using a Schmidt hammer, Stephenson and Kirk (2000) determined that rock strength had been decreased by 50% during weathering on shoreline platforms. A comparison of weathered versus fresh rock rebound values must be done to assess weathering. The degree of weathering of boulders was not the aim of this project.

Errors Associated with the Schmidt Hammer

The Schmidt hammer regularly requires calibration and maintenance. A series of tests are conducted on a test steel anvil (Type-N hammers should have rebound values of 78). A ratio of test values up are 78 is used to calibrate field test values. A type-N Schmidt hammer commonly yield values from 30-75. For values below 30 a Type-L Schmidt hammer should be used. Numerous site characteristics can lead to erroneous rebound values. Changes in mineralogy and grain size will affect weathering rates and thereby rebound values. Effects of aerial exposure such as surface texture will impart variable rebound values (McCarrol, 1994).
CHAPTER XIII

RESULTS

Eleven seismic lines were run during winter 2000/01 (Figure 4). Data were recorded in the SEG-2 format with automatic gain control (signal enhancement). The number of shot gathers (stacks) per line was variable for each line. Longer lines/longer shot offset necessitated multiple stacks to detect/resolve first arrivals at the most distant geophones. Shot gathers were sampled at 2 ms (maximum sampling rate allowed by refraction interpretation software). A higher sampling rate would have provided better resolution and easier first break picking. The testing areas were free of urban noise (cars, electrical wires, etc.) with the exception of an occasional low flying prop driven airplane. The rustle of plants due to wind (background noise) was detected by the geophones and did appear on records. Stacking effectively cancelled out the background noise due to its irregularity as compared to repeated shots. Testing during the early morning and evening (periods of low wind) yielded the least amount of background noise.

Seismic Refraction Lines

WINSISIM was used to calculate the layer velocities and thicknesses at each shot point along a seismic line. Some lateral inter-layer velocity changes did occur but were not significant enough to imply errors in calculation. Physical properties are likely to vary drastically which could lead to data that were surprising (Radzevicius and Pavlis, 1999). Variable layer thickness did occur and is to be expected, especially across topographic changes.

The field methodology and characteristic shape of travel time curves indicate that all seismic lines of this study could be resolved as three layers. Many midpoint shot travel time curves detect only two layers and a third layer was exhibited on end or offset shot travel time curves. On rare occasions, end offset shot travel time curves suggest a fourth layer. This fourth layer was omitted and thought to be anomalous because a fourth layer was not displayed in reverse shots. The layering is as follows; a surface layer (Layer-1), an intermediate layer (Layer-2), and a terminal layer (Layer-3). The velocity in Layer-1 ranged
from 514-1230 m/s with a mean of 885 m/s. Layer-1 depth was from 5-35 m and averaged 19 m. Layer-2 resolved velocities form 1094 to 3495 m/s, mean at 2032 m/s. Layer-2 was as thin as 5 and as thick as 50 m and averaged 23 m. The velocities in Layer-3 were from 1600-6282 m/s. Due to the attenuation of seismic energy, the thickness of Layer-3 cannot be resolved and is beyond the scope of this study.

To assess microclimatic induced changes, values for layer velocity and thickness were averaged for each line, and grouped either in terms of microclimate or facies (Table 3, Figure 18). The Mediterranean hot summer climate mean values are; CSA; Layer-1 775 m/s and 14 m thick, Layer-2 1946 m/s and 21 m thick, and Layer-3 4542 m/s (Figure 19). In the semi-arid hot microclimate, BSH, mean values are; Layer-1, 1082 m/s and 23 m thick, Layer-2, 2146 m/s and 20 m thick, and Layer-3, 4249 m/s (Figure 19). In the arid-hot microclimate, BWH mean values are; Layer-1, 872 m/s at 24 m in thick, Layer-2, 2061 m/s at 29 m of thick, and Layer-3, 4941 m/s (Figure 19).

Facies controlled changes should be evident with respect to mean values. The mean for the hornblende-biotite facies, H-B, are; Layer-1, 715 m/s at 15 m thick, Layer-2, 2534 m/s at 29 m thick, and Layer-3, 5158 m/s. Only one line was run in the large-biotite facies, L-B (may not be representative of the facies). Layer-1 along this line is 5 m thick at 575 m/s, Layer-2 is 12 m thick at 2534 m/s, and Layer-3, 3188 m/s. Most lines (8) were run in the small-biotite facies, S-B. The mean for Layer-1 for this facies is 966 m/s at 22 m thick, Layer-2, 1980 m/s at 23 m thick, and Layer-3, 4595 m/s.

**Student’s T-Test Analysis of Populations**

The Student’s T Test is a statistical means of determining if two distinct populations are of the same underlying population. The T Test was used to compare the velocities of Layer-1 in the Mediterranean hot summer, CSA, microclimate versus the same population in the semi-arid hot, BSW, microclimate. Applying the T-Test to two selected populations will yield a T-Value (Table 4). The T-Value will then be used to calculate the probability that the two populations are of the same underlying population. A probability of 0.05 or less indicates that the two populations could of come from the same larger population. The sample populations are small, three to five members each. Increasing the population size probably decrease the P-Value and therefore suggest that the two populations were from the same underlying population.
### Table 3. Velocities and Depths of Seismic Refraction Lines

#### Refraction Values by Microclimate

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<tr>
<th>Line #</th>
<th>Microclimate</th>
<th>Facies</th>
<th>Layer-1 Velocity, m/s</th>
<th>Layer-2 Velocity, m/s</th>
<th>Layer-3 Velocity, m/s</th>
<th>Thickness Layer-1, m</th>
<th>Thickness Layer-2, m</th>
<th>WF, m</th>
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#### Refraction Values by Facies

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Figure 18. Velocity Vs Depth
Figure 19. Velocity Vs Depth by Microclimate
Schmidt Hammer

Schmidt hammer testing was conducted in the Mediterranean hot summer, CSA (hornblende biotite facies) and arid-hot microclimates, BWH (small biotite facies) to support/assist seismic interpretations (Figure 4). Schmidt hammer testing was completed at four locations, each with five individual test areas. To obtain representative readings on unweathered to very slightly weathered granite (test surfaces polished with electric grinder), only the upper 50% of readings were analyzed (Katz et al., 2000). The variability of all readings may be used as a measure of differential weathering within a small area.

Schmidt sites 1 and 2 (CSA, H-B) yielded an average rebound value of 50 and 60 respectively (Table 5). Correlations from Katz et al. (2000) yielded the Young’s modulus E, uniaxial compressive strength μ, density ρ, and Lame’s constant λ based on the rebound value. The seismic velocity was then determined from Birch’s Law and the calculated density, ρ. The calculated velocities range from 4483 m/s (Site #3) to 5332 m/s (Site #4) with intermediate values at 4789 m/s (Site #1) and 5461 m/s (Site #2).

Table 5. Schmidt Hammer Data and Bulk Rock Properties

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<th>mu Uniax. CmpStr, Mpa</th>
<th>lamda Lame's constant</th>
<th>rho Density, g/cc</th>
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During T-Test analysis, a P-Value of 0.05 or less was not encountered, it can therefore be stated that each population is unique in itself or that the sample populations are to small.
CHAPTER XIV

DISCUSSION

The findings of this study, seismic velocity and layer thickness, were intended to quantify the effects of the present day climate on the existing regolith.

Most data (few exceptions) suggested three layers beneath the seismic line. The depths to layering are not limited to soil profiles of Bowman (1974), Fortin (2000), and Mitchell (2000). The depths to layering presented in this study are interpreted to represent major changes in structural constraints rather than the petrological/chemical constraints within a soil profile.

Layer-1, Soil and Grus with Weathered Corestones

Layer-1, as calculated by this study, is between 5 and 35 m thick (Figure 20). It is not interpreted as the “thin soil cover in La Posta loamy coarse sands which typically is 1-2 m or less” (Bowman, 1974) but, as a layer inclusive of all alluvium, colluvium, in place derived La Posta soils, grus/saprolite, and unlocked corestones (“floaters”). “Floaters” pertains to buried boulders wholly encased in friable saprolites or soils. “Locked” corestones are those with some degree of attachment to the substrate (these terms are largely geotechnical vernacular). The variability in thickness can be likened to the variability of corestones exposed at the surface within the La Posta pluton. The velocity in Layer-1 varied from 514-1230 m/s with an average of 885 m/s, and correlates with surface seismic variability of Radzevicius and Pavlis (1999) (400-700 m/s), which these authors interpreted as soil and grus. In the case of Layer-1, the term “layer” is a stretch of conventional usage as a “homogenous, isotropic, elastic slab of material” (ibid).

Borehole seismic studies in a similar terrain (Fletcher et al., 1990) yield interpretations of structure and its influence on seismic velocities. Surface velocities begin at 300 m/s and increase sharply to 4800 m/s at 70 m depth. Velocities are very low for granite but must be due to weathering of the granite near the surface.
Figure 20. Weathering With Depth. Schematic depicting vertical weathering. The base of Layer 1 and the water table (WT) occurs from 5 to 35 m in depth. The weathering front (WF) occurs from 17 to 85 m in depth.
Layer-2, Water Table and Decreasing Weathering with Depth

The top of Layer-2 most likely represents the groundwater surface. At all sites (with the exception of Line # 2) the top of Layer-2 represents a feasible estimation of the groundwater surface. A review of site parameters, topography, vegetation, and groundwater recharge indicates that groundwater at these depths is probable. Line #2 however was located along a slight ridge. The depth to the top of Layer-2, along this line is 5 m, a depth that is too shallow for groundwater. The surface of Layer-3, at 17 m, could represent the groundwater surface at this location.

The proximity (256 m to the southwest) of Line #3 to the Hubbard domestic well suggested a correlation of known groundwater elevations (well data) to interpreted groundwater (refraction). The depth to the top of Layer-2 at line #3 is 19 m and is shallower than the mean depth to groundwater, 30.2 m, at the Hubbard domestic well. The discrepancy, 11.2 m, between the interpreted groundwater depth and actual groundwater level is not totally unexpected. The gradient between the two sites, 4.3 cm/m, could occur as a result of drawdown from production, regional fracture density, or topographic influences.

Aside from groundwater, Layer-2 also involves the downward transition from locked spheroidaly weathered corestones and intervening saprolite at the top down to fractured and blocky granite with weathering only along joints and fractures. The base of Layer-2 could represent localized horizontal jointing (Lower, 1977) and weathering along it (Radzevicius and Pavlis, 1999). Layer-2 varied in thickness from 7 to 50 m with a mean at 19 m. Velocity varies from 1049-3379 m/s and averages 2032 m/s. Findings here are similar to Radzevicius and Pavlis (1999) who found “a highly heterogeneous layer in the 2-15 m depth range with velocities from 1600 to 2700 m/s”. At a depth of 15 m, “a zone of partially weathered rock and corestones embedded in saprolite was encountered.” Fletcher et al. (1990) found shear wave attenuation was significant at 17.5-40 m depth with usual attenuation above 50 m. “Rock structure is sufficiently complicated that body waves are being converted (SH to SV at oblique incidence) very close to surface”, possibly due to “floating” corestones. Coring at this site (Pinon Flat) found weathering extended to 30 m.
Layer-3, Unweathered Granite

The weathering front is delimited by the interface at the base of Layer-2 and top of Layer-3. Velocities for Layer-3 are 1600-8855 m/s with a mean at 4564 m/s. Higher velocities (>5000 m/s) are indicative of unweathered granite (1600 m/s is not considered unweathered granite). The mean depth to the top of Layer-3 was 42 m and varied from 18-85 m. The character of Layer-3 where velocities top 5500 m/s should be like that of fresh pristine La Posta granodiorite. Fracturing within rocks of this character is likely (Lower, 1977) but fractures/cracks would be unweathered and narrow with little to no dislocation of adjacent rock masses.

Radzевичius and Pavlis (1999) resolved a jump in seismic velocity of 3300 m/s to 5400 m/s at 60 m depth (combined refraction/reflection study). Strong reflection represents the base of the most heavily weathered region and could represent weathering along a sheeting joint. This change is not distinct but gradational. Early arrivals may represent the tops of more intact bodies of granite. Seismic velocity at 120 m depth was 5400 m/s (Fletcher et al., 1990). “An abrupt decrease in drilling rates and degree of alteration of biotite and chlorite to smectite clays were found to occur at depths of 70-80 m at Hi Vista” (Fletcher et al., 1990).

An irregular weathering front along adjacent masses of similar rock (age, origin, and mineral assemblage) could be a reflection of biotite content (Isherwood and Street, 1976). Variation in biotite content may reflect incomplete melting/mixing during emplacement of the magma. Biotite content varies with facies and is not localized within the La Posta pluton.

Fisher et al. (1990) concluded that there is no one to one correspondence between crack density and velocity. They studied a small set of fractures at 76 m and one larger set at 104 m. Seismic velocity at 70 m depth was 4800 m/s. It increased to 5400 m/s at 160 m. They found 5600 m/s in unfractured granite vs. 5400 in fractured granite (both deep > 120 m). The upper 50 m if not 20 m, is responsible for the observed seismic attenuation. It is however unclear as to whether attenuation occurs in weathered grus between buried boulders near the surface or in cracks that are perhaps partially filled with water. In the Laguna Mountain area, (not the La Posta pluton, but a like intrusive) the upper saturated zone involves groundwater circulating through alluvium, weathered mantle (saprolite), and fractured bedrock. The base of this zone is 90-125 m (Lower, 1977).
Facies Controlled Weathering

Of the eleven lines, one lies within the large-biotite facies, two within the hornblende-biotite facies, and the remaining eight are within the small-biotite facies. The distribution of test locations is skewed toward the small-biotite facies (73% of the data) and precludes a discussion of weathering with respect to facies changes within the pluton. The velocities and layer thickness are largely similar when averaged for each facies.

Microclimate Controlled Weathering

When the depth of weathering for each microclimate is averaged, the weathering front (top of Layer-3) shallows to the west as wetter microclimates are encountered at higher elevations. The velocity in Layer-3 is highest in the arid hot climate, but velocity trends were not found in the upper two layers. Layer-1 was found to be the thinnest, averaging 14 m, in the wettest microclimate (CSA). The base of Layer-1 in the Mediterranean Hot summer climate probably represents the top of the water table.

The western region of the study area represents the maximum plant cover, precipitation, and elevations. Hence, the region possesses the highest infiltration, leaching, and plant uptake of nutrients. Within the Mediterranean hot summer climate, weathering and the depth to the weathering front appear to be controlled primarily by the effective decomposition of granite and saprolites by high infiltration rates and plant nutrient uptake. In other words, weathering within the Mediterranean hot summer climate is chemically controlled and as a result should yield the deepest weathering front.

In contrast, in the drier climate of the eastern region a shallower moisture penetration and shorter time to runoff occur (Canton et al., 2001), and as a result a high degree of percolation and chemical weathering has not affected this region. The rainfall events within the dry climate within the eastern region may be below the threshold for runoff and erosion (Canton et al., 2001). Hence, the depths to the weathering front should be the shallowest.

Why then is just the opposite observed?

Though not clear at this time, the answer to the above question likely lies within the concepts of transport- and weathering-limited systems. Transport-limited and weathering-limited systems define equilibrium conditions. In weathering-limited regions erosion and mass wasting proceed at a ratio faster than or equal to soil development. In contrast, in
transport-limited regimes, soil development proceeds at a faster rate than do erosion and mass wasting.

Hence, one possible explanation of observations made during this study would involve long-term evolution of the weathering front since latest Cretaceous time. In this scenario a thick zone of weathering evolves across the Peninsular Ranges during a more humid climates in the Late Cretaceous and possibly during the Pleistocene. During development of the Salton trough and Gulf of California (8 Ma to present), this zone of weathering was disrupted by extensional faulting and down dropping of the eastern part of the Peninsular Ranges (Figure 21). Hence, the shallower weathering front in the western part of the study area reflects uplift, erosion, and mass wasting within a weathering-limited regime as this region attempts to adjust to the new and evolving tectonic and climatic regime (Figure 22). In contrast, the depth to the weathering front in the eastern region may reflect long term weathering within a long-term transport-limited regime. Clearly we have much to learn regarding short versus long term evolution of weathered materials in the Peninsular Ranges.

**Schmidt Hammer**

The findings (Table 4) generated by using the Schmidt hammer correlations of Katz et al. (2000) were intended to constrain the mechanical properties of unweathered La Posta granodiorite at each test site. The results however suggest that Schmidt hammer testing of this study reflects weathered boulders of varying degrees. The highest calculated mechanical rock properties occur at Site #4 (easternmost site) and most likely reflect alteration by case hardening. At this site, intragranular disintegration is replaced by reprecipitated calcite that fills previously weathered cracks and voids. Low mechanical rock values, for example Site #1, occur within the Mediterranean hot summer climate (wettest) where case hardening is limited by constant flushing. Site #1 may also be a reflection of the proximity of the test area to the ground. At this site, Schmidt testing occurred directly on an outcrop near ground level. Proximal lichen cover (on rock surface) and adjacent plant growth contributed to accelerated weathering at this site. Site #3 was also conducted near the ground surface on a bedrock outcrop. Testing on sites #2 and 4 were on well exposed and elevated boulder surfaces where plant weathering is nil and rock properties are markedly higher. The testing surfaces at sites #2 and #4 were on prominent freestanding boulders. Boulders generally represent the
Figure 21. Development of Weathering Mantle, Faulting, and Microclimates
Known depth to layers is plotted beneath each line (in red). Inferred depths to layers are illustrated. Inset map shows surface trace of cross-section. (Vertical exaggeration is approximately 30X).

Figure 22. Cross-Section Line #2 to Line #10.
most weathering resistant components of bedrock. The calculated mechanical rock
properties at these sites are most likely the closest to unweathered La Posta granodiorite or
represent those remnants of localities of most resistant bedrock. Weathering resistance could
be a reflection of local grain size or mineralogy variation.

Schmidt hammer testing of this study was conducted one day following a recent rain
and snowstorm. Moisture was observed to rise to the surface (from within the rock) of
recently prepared (polished with electric grinder) test surfaces at sites #1 and #3. The
proximity to the ground surface at these sites contributed to the availability of intragranular
pore water. Testing at these sites could therefore reflect saturated rock mechanical properties
whereas testing on sites #2 and #4 are closer to dry rock properties. While we can assume
that bedrock at depth is most likely saturated, the correlations of Katz et al. (2000) were
generated for dry rocks. In addition, saturated rocks most likely involve a different Schmidt
hammer response. The Schmidt hammer was developed to test cured (dry) concrete. A
review of Schmidt hammer related literature did not reveal a comparison of dry and saturated
rock properties.
CHAPTER XV

CONCLUSION

Seismic refraction studies of the La Posta pluton reveal the influence of weathering in three microclimatic zones. Analysis of refraction data conducted as a part of this study resolve layering indicative of decreasing weathering with depth and has been resolved as three layers. The distribution of study sites however did not allow for a correlation in a change in weathering with respect to petrologic facies of the pluton. Study sites were instead selected to reflect microclimatic induced changes. Schmidt hammer testing on outcrops sought to constrain bedrock mechanical properties and assist seismic interpretation. Schmidt hammer values were found to be highly variable and it was determined that more testing would be necessary to constrain rock properties.

Seismic refraction studies have segregated the regolith into two layers; Layer-1, soil and grus with weathered corestones, and Layer-2, in-place moderately weathered closely spaced corestones grading downward to minimally weathered blocks, the top of which could represent the groundwater surface. Correlating the known groundwater elevation at the Hubbard Domestic well, (30.2 m) and the interpreted groundwater surface at Line #3 (19 m) suggested that variation of the groundwater surface was to be expected over short distances (256 m between well and seismic line). Velocity and thickness were; 514-1230 m/s and 5-35 m and 1049-3379 m/s and 7-50 m, for layers 1 and 2 respectively. The bedrock (1600-8855m/s) is termed Layer-3, the top of which (18-85m depth) marks the downward limits of the weathering front, which may be localized along horizontal jointing.

The regolith atop the La Posta pluton may have developed over the long term during the late Cretaceous through early Eocene and Pleistocene under a possibly warmer and wetter weathering climate (Peterson and Abbott, 1974). The shallowest mean depth to the weathering front (top of Layer-3) was found in the wettest microclimate (Mediterranean hot summer) and is contrary to conventional wisdom which suggests that areas of greatest precipitation should have the deepest weathering front. Westward thinning of the regolith can be explained as the result of its development during uplift and associated erosion and
mass wasting as the eastern region was down-dropped during development of the Salton Trough. In short, the thickness of the weathering mantle across the La Posta pluton suggests that the western area of the pluton developed under a weathering-limited regime while the eastern area reflects a transport-limited environment.
REFERENCES


Girty, G. H., 2000, The onset of chemical weathering within the humid-arid transition. Grant proposal, unpublished.


APPENDIX

SOILS DESCRIPTIONS
Subcategories of the La Posta Soil Series, Bowman, 1973

LaE2 (loamy coarse sand 5-30% slopes eroded). A “gently rolling to hilly soil on strongly dissected plateaus and terraces with an average slope of 6%”. Fertility is described as low, roots penetrate 64-89 cm. Permeability is rapid, and runoff is low with a moderate erosion hazard.

LaE3 (loamy coarse sand 5-30% slopes severely eroded). This moderately sloping to moderately steep soil is 41-69 cm thick over weathered granite. Seventy five percent of the surface soil has been eroded due to rill and gully erosion. Soil water capacity is 3-5 cm. Erosion hazard is high and runoff is medium.

LcE (rocky loamy coarse sand 5-30% slopes). This soil is found on moderate to moderately steep slopes and is not eroded. Soil is form 41-81 cm over weathered granodiorite. Rock outcrop covers 5-10% of the surface. Water holding capacity is 3-5 cm, runoff is medium.

LcE2 (rocky loamy coarse sand 5-30% slopes eroded). This soil is 41-76 cm over weathered granodiorite on moderate to moderately steep slopes. Runoff is medium and erosion hazard is moderate. Soil water capacity is 2-5 cm.

LcF2 (rocky loamy coarse sand 30-50% slopes eroded). This steep soil is 41-76 cm over weathered granite. Runoff is rapid and erosion hazard is high. Water capacity is 3-5 cm. Rock outcrops cover 5-10% of the surface.
ABSTRACT

Seismic refraction studies were conducted on the Cretaceous La Posta granodiorite pluton, San Diego, California, to determine the depths of weathering across three microclimatic zones; Mediterranean hot summer, semi-arid hot, and arid. Data have been resolved as three layers. Layer-1 consists of surfical La Posta derived soils, alluvium, colluvium, grus, and shperiodally weathered boulders. Layer-2 includes an upper surface defined by the top of the water table and represents a transition from highly weathered boulders and intervening grus to fractured blocks of granite with slightly weathered intervening grus with depth. Layer-3 represents unweathered granodiorite. The top of Layer-3 coincides with the terminal depths of the weathering front. A Type-N Schmidt Hammer was used on bedrock outcrops in an attempt to constrain mechanical properties and aid in seismic interpretation. Schmidt hammer data were found to be highly variable and it was determined that strict testing conditions should be followed and more data were needed for good correlation to seismic data.

The weathering mantle atop the pluton was developed from the latest Cretaceous to recent time. Seismic refraction lines indicate that the thinnest regolith (shallowest weathering front) lies in the wettest and coolest microclimate (Mediterranean hot summer) while the thickest regolith lies in a drier and hotter arid microclimate. The westward shallowness of the weathering front resulted from long-term evolution culminating within a weathering-limited regime that developed over the last 8 Ma as the Salton trough evolved. Uplift of western regions contributed to increased rates of erosion and mass wasting relative to soil development in the western part of the pluton while the same processes occurring within the eastern areas were not as effective.