# SECTION THREE:

# GEOLOGY AND GEOMORPHOLOGY

## 3.1 GENERAL STATEMENT

Geology is one of the principal factors that govern the geomorphic and hydrologic processes within a watershed. Geology includes rock type and sequence (lithology and stratigraphy); soils; tectonics (faults, seismicity, and folds), and mass wasting (landslides).

The lithology and stratigraphy of rocks in the La Honda watershed strongly influence the channel form and the composition of the sediment in the streambed and banks. The lithology of the bedrock also influences the extent of soil development, shear strength, porosity, depth, vegetation productivity, and erodibility, as well as the depth and style of landslides, and the magnitude of ground acceleration during earthquakes. The rates of tectonic uplift affect the stream gradient and rate of downcutting, and extent of bank/bed erosion.

Geologic ages are noted herein in millions of years (Ma) for older rocks or events, and in years before present (BP) for younger. A Geologic time scale is included in Appendix W.

## 3.2 PREVIOUS WORKS

Numerous works have provided invaluable background to this study. Brabb et al. (2000) mapped the bedrock units in the La Honda area. Sarna-Wojcicki et al. (1991); Turner (1970); and Fox et al. (1985) determined the ages of the Mindego basalt and the Tahana Member of the Purisma Formation. Wagner and Nelson (1954) compiled the San Mateo Area Soil Survey based on the USDA-SCS soil classification system.

Wieczorek (1982) discussed the weathering characteristics of bedrock in the area, and their effect on the style and extent of landsliding. Wieczorek (1984) mapped landslide parameters in the La Honda area. Wieczorek (1984 and 1987) found that landslides were triggered by a combination of rainfall intensity and duration. Wilson and Wieczorek (1995), and Cannon and Ellen (1985) developed numerical models relating rainfall and hillslope pore water pressure to the initiation of debris flows. Wieczorek and Keefer (1984) described a La Honda area landslide triggered by the Morgan Hill, CA earthquake on April 24, 1984.

Brabb and Olson (1986) compiled a map of fault traces and earthquake epicenters in San Mateo County. Clahan and Wright (1994) calculated an average annual slip rate of 20±5 mm/yr (0.8±0.2 in) for the San Andreas fault near Woodside, California.

## 3.3 LITHOLOGY AND STRATIGRAPHY

### Bedrock Units in the La Honda Watershed

As mapped by Brabb et al. (2000), rock units in the La Honda watershed include the Butano Sandstone (Middle and Early Eocene), Mindego Basalt (Oligocene and/or Miocene), undifferentiated Lambert Shale and San Lorenzo Formation (Late Eocene to Early Miocene), Monterey Formation (Middle Miocene), and the Tahana and Pomponio Members of the Purisima Formation (Late Miocene to Pliocene) (Figure 3-1). The following descriptions of bedrock units in the La Honda watershed are mainly from Brabb et al.:

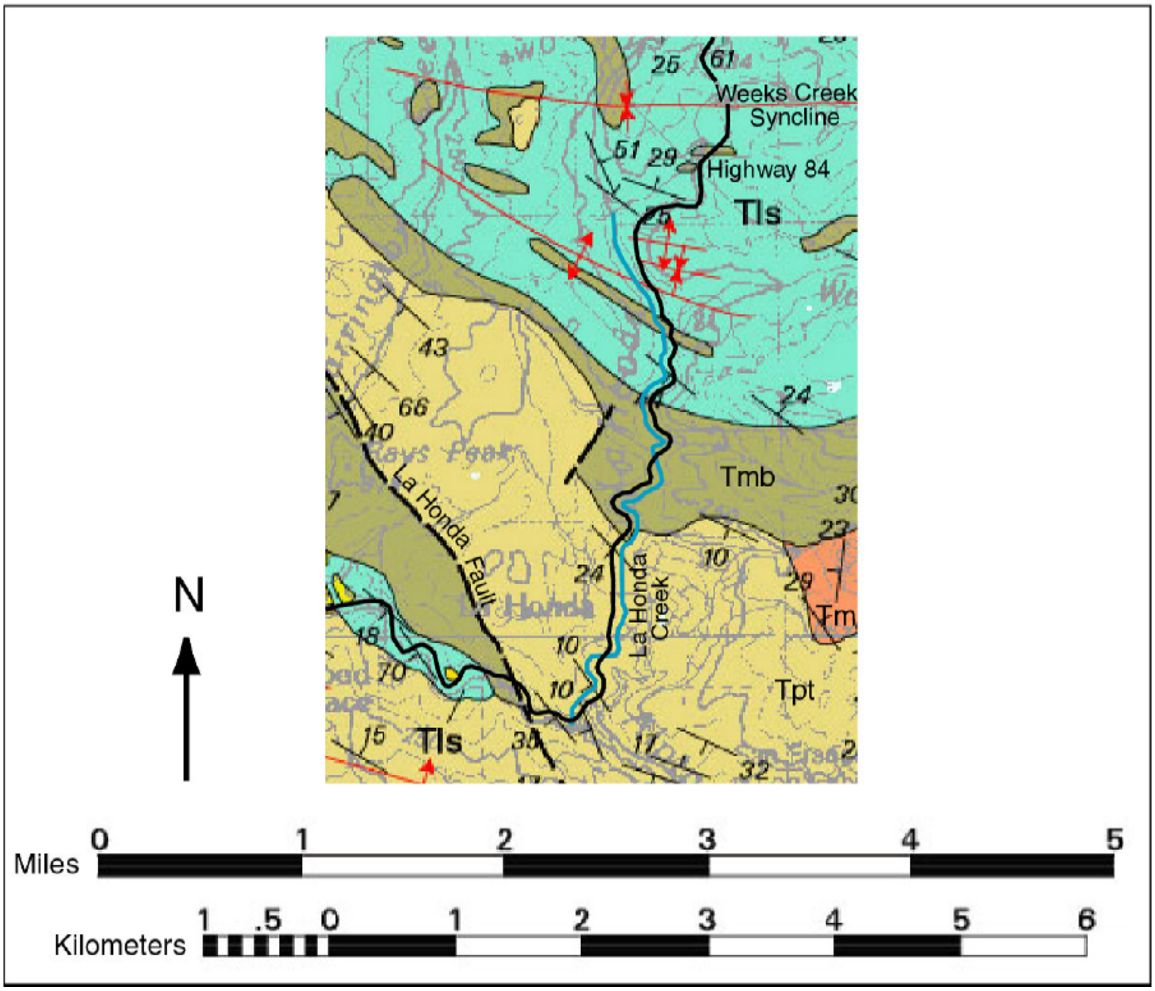


**Figure 3-1.** Geological map of the La Honda Creek study area (from Brabb et al., 2000). Highway 84 is indicated by a black solid line, La Honda Creek by a solid blue line.

<u>Butano Sandstone</u>

The Butano Sandstone is gray to buff, very fine- to coarse-grained arkosic sandstone in thin to very thick beds, interbedded with gray to brown mudstone and shale. The amount of mudstone and shale varies from 10% to 40% of the formation volume. Conglomerate containing boulders of granitic and metamorphic rock and smaller, well-rounded clasts of quartzite and porphyry, is present locally in lower part of section.

<u>Mindego Basalt</u>

The Mindego Basalt is primarily gray to brown, fine-grained, basaltic breccia, with lesser amounts of tuff, pillow lava, and flows, and minor sandstone and mudstone. Volcanic rocks have a maximum thickness of 120 m (394 ft) but occur as irregular masses. Intrusive rock is dark greenish gray brown, and medium to coarsely crystalline. It commonly occurs as spheroidally weathering, tabular bodies as much as 180 m (591 ft) thick intruding older sedimentary rocks. The Mindego Basalt has yielded a minimum Potassium/Argon age of 20.2 +/- 1.2 Ma (Turner, 1970, recalculated by Fox and others, 1985).

Lambert Shale and San Lorenzo Formation - Undivided

The Lambert Shale and San Lorenzo Formations consist of brown, gray, and reddish mudstone, siltstone, and shale with beds of fine- to coarse-grained sandstone. The Lambert Shale is generally more siliceous than the San Lorenzo Formation, but where out of stratigraphic sequence and without fossils, the two units cannot be distinguished.

Monterey Formation

The Monterey Formation is gray, brown, and pale-to-white, porcelaneous cherty shale and mudstone, impure diatomite, calcareous claystone, with minor siltstone and sandstone near base. The thickness ranges from 120 to more than 600 m (394 to more than 1970 ft). The Monterey Formation closely resembles parts of the Pomponio Member of the Purisima Formation.

Purisima Formation, Tahana Member

The Tahana Member of the Purisima Formation is greenish gray to white or buff, medium- to very fine-grained sandstone and siltstone, with some silty mudstone, and local tuff. The maximum thickness is 655 m (2150 ft). A tuff bed has been tentatively assigned an age of 2.6 Ma (Sarna-Wojcicki et al., 1991).

**Bedrock Units in the La Honda Creek Channel (As mapped on Plates 1A-C)**

The Tahana Member of the Purisima Formation, the Mindego Basalt, and the Lambert Shale and San Lorenzo Formation are the only units exposed in the La Honda Creek channel. Each of these bedrock units has differing engineering properties, as summarized in Table 3-1. Because the engineering or ecological characteristics of the sedimentary units are similar, for the purposes of this report only two bedrock units were mapped: undifferentiated Tertiary sedimentary rocks and the underlying Mindego Basalt (Plates 1A-C).

We performed Schmidt rebound hammer tests on all the bedrock units following the conventions discussed in Williamson (1984) – Unified Rock Classification System. Based on the quality of the impact of a one-pound ball peen hammer, the unconfined compression strength can be estimated quite accurately (Appendix X). This value is useful in that it describes a rock's unconfined, load-bearing strength.

Tertiary Sedimentary Rocks, Undifferentiated

Tertiary sedimentary rocks exposed within the La Honda Creek channel include pale gray to brown, fine-grained sandstone, siltstone, and mudstone (Figure 3-2). With the exception of some sandstones that are moderately indurated, these rocks are poorly cemented and poorly indurated. Based on crater quality (CQ) response to the Schmidt rebound hammer test, the unconfined compressive strength is fairly uniform at 7-21 MegaPascals (MPa) (1000 to 3000 psi) throughout the study reach.

Joint sets are closely to moderately spaced (30 to 300 mm or 1.18 to 11.8 inches) on intersecting planes, and have tight apertures. Deep seated, paleo-landslides have disrupted large sections of this unit, producing large volumes of colluvium that deliver fine-grained sediment to the creek.

Clays derived from the Lambert Shale contain up to 65% montmorillonite, while those from the Tahana Member of the Purisma Formation contain up to 90% montmorillonite (Wieczorek, 1982). Montmorillonite is an unstable "smectite" clay that swells upon wetting and shrinks upon drying, causing the rock to decrepitate (fall apart into small pieces). Repeated cycles decrease the rock's shear strength, making the slopes more prone to landsliding. Also, this process probably contributes to the embeddedness of the stream substrate that is problematic to salmonid spawning (See Section 6).

Basalt

Basalt of the Mindego formation forms the most stable banks along La Honda Creek. Most of the rocks are well indurated, dark colored, finely crystalline. Intrusive and extrusive rocks are usually difficult to differentiate, but in several locations in the creek, lava flows are intercalated with gravel and locally, sections are vesicular with amygdules of quartz. In places, the basalt is brecciated and hydrothermally altered: shot through with quartz and calcite veins and areas of sheared arsenopyrite, pyrite, and iron gossan. The basalt is highly fractured by multiple, intersecting sets that tend to be open to partially healed with dark brown to black iron oxides, calcite and quartz. Schmidt rebound hammer tests were dent to crater quality (DQ-CQ) indicating that the unconfined compressive strength of the basalt varies widely from 7 to 55 MPa (8,000 to 1,000 psi). Brecciated sections weather rapidly to clay and readily host shallow debris flows.

**Surficial Units in La Honda Creek (As mapped on Plates 1A-C)**

Surficial units mapped along the La Honda Creek channel are identified as Pleistocene to Holocene colluvium, Holocene terrace deposits, Holocene bedded silt, modern stream sediment, and engineered and unengineered fill (Plates 1A-C). Stratigraphic relationships (both vertically and/or horizontally) between these units are complex and often involve two or more units. Modern stream deposits are not included as map units, but are discussed in Section 6. Designations based on the Unified Soils Classification System (USCS) are used throughout (e.g. CL = low plasticity clay).

Shear strength is one of the main mechanical parameters that determines the resistance of slopes to landsliding and of stream banks to slumping and erosion. Usually, the shear strength decreases with increasing water content. We conducted a field test using a Soil Test Pilcon DR-393 tor vane to determine the in-situ shear strengths of sands and fine-grained soils in the La Honda Creek channel under varying water contents (Appendix B, Figure B-1). To conduct the test, vanes having known surface areas are inserted to varying depths into soft soils. The knob is rotated by hand as the dial measures the torque required to rotate vanes. The torque and surface area values are then converted to shear strength.

Colluvium

Colluvium in the La Honda Creek channel formed by landslide processes, particularly debris flows. Colluvium is most abundant in the northern reach, where landslide deposits make up nearly 50 % of the stream banks. Regardless of whether it is derived from basalt or from sedimentary bedrock, the unit has similar characteristics. The colluvium consists of 30 to 60 % angular fragments of bedrock ranging in size from 0.5 to 5 cm (1.97 – 19.7 in), in a matrix of clayey silt. Saturated tor vane shear strengths average 18.9 kiloPascals (kPa) (395 psf) (Appendix B). Based a field test, the soil has high plasticity, medium to high toughness, no dilatancy, and high to very high dry crushing strength. The matrix produces pronounced shrinkage cracks when dry indicating it also has high shrink-swell potential.

Terrace Deposits

Terrace deposits are situated topographically higher than the modern channel sediments of similar origin, and occur throughout the study reach (Figures 3 and 4). Based on visual inspection, terrace deposits consist predominately of boulders, cobbles and gravels (GW); the $D_{50}$ (median grain size) of these sediments appears to be substantially larger than that of the modern channel deposits, lacking the finer fractions due to post-depositional winnowing. Clasts are mainly fragments of the Mindego Basalt unlike the modern stream gravels that contain cobbles and boulders derived from the Tertiary sedimentary bedrock. The absence of sedimentary clasts is consistent with field observations that the sedimentary rock are unstable and readily decrepitate to granule-sized particles when exposed on the bars and are readily swept away during high flows. Presumably, the terrace deposits were laid down during flood events in the early Holocene when the creek had a much higher discharge and greater competence required to transport the larger clasts.

Bedded Silt

Thick deposits of massive to well bedded silt occur discontinuously, especially in the northern reach of the channel, consistently overlying the colluvium. The silt unit is pale to dark brown, and locally has thin interbeds of organic-rich sediment. The silt is of uniform grain size (ML-MH), lacking the fragments of bedrock diagnostic of colluvial deposits. Based on field tests, the silt has low to medium toughness, low to medium plasticity, moderate dilatancy, and low dry crushing strength. Saturated tor vane shear strengths average 22.8 kPa (477 psf) (Appendix B). The marked stratification may be due to detrital layering during deposition, or may represent moderately developed humic A and cambic B soil horizons. The uniform, fine grain size; well developed bedding; discontinuous occurrence; and stratigraphic position indicate that the silt was deposited in quiet water ponds that formed upstream of temporary dams that blocked the flow such as debris flows, or man-made structures such as were used to create mill ponds.

Modern Channel Sediment

Modern channel sediments in La Honda Creek consist of poorly graded boulder, gravel, and sand mixtures derived from local bedrock. In areas dominated by sedimentary rocks, the channel sediments can have as much as 90% sedimentary clasts, but usually, the most common (up to 99%) coarse constituent is Mindego Basalt. Sandbars occur downstream from recent landslides, and silty overbank deposits overlie some of the older terraces following high-flow events. For a full discussion of the grain size distribution and other characteristics, refer to Section 6.


**Figure 3-2.** Tertiary Sedimentary Rock map unit in bank of La Honda Creek (Plate 1A).

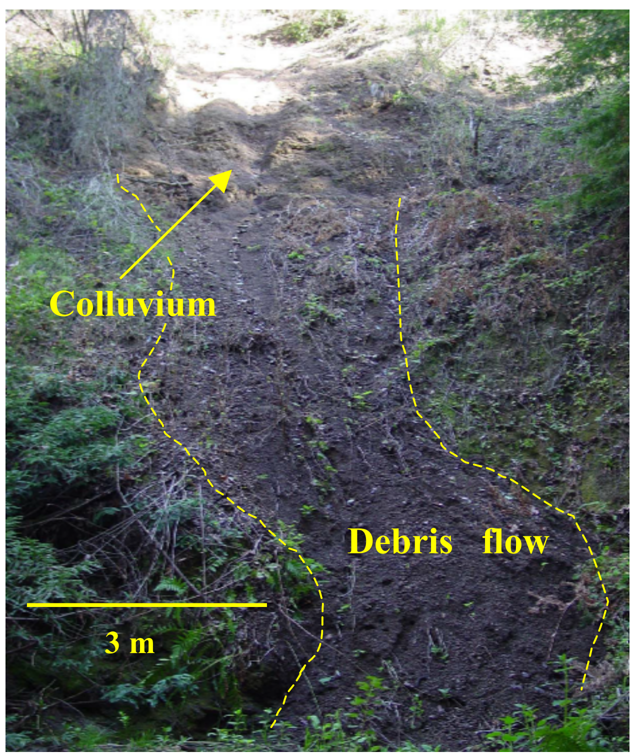


**Figure 3-3.** Colluvium map unit exposed by small debris flow, La Honda Creek channel. Such relationships demonstrate that slopes are repeatedly mobilized (Plate 1A).

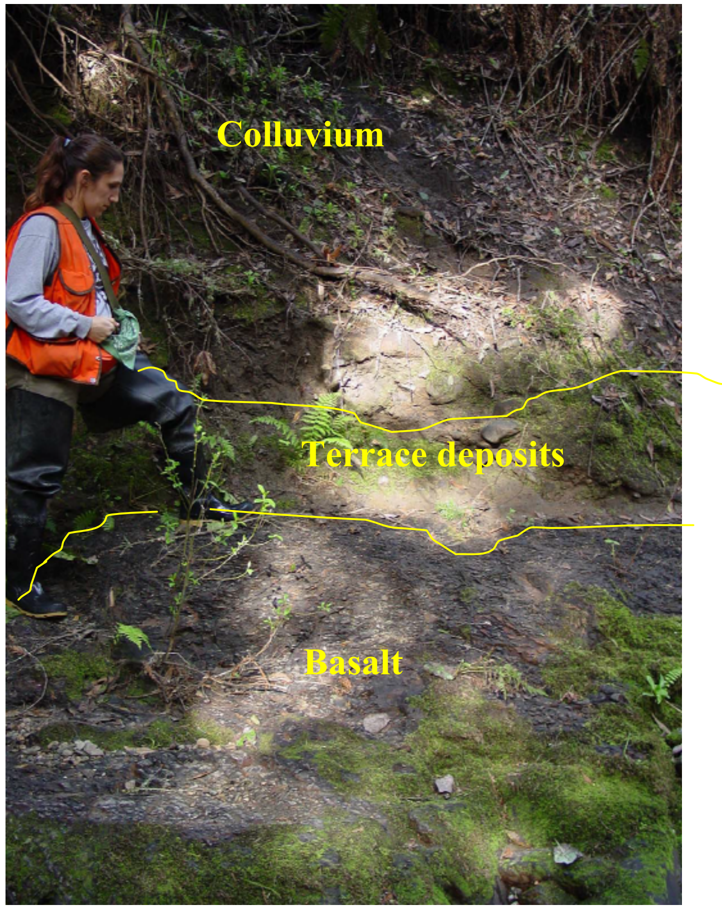


**Figure 3-4.** Relationship between Basalt (below), Terrace deposits, and Colluvium map units in bank of La Honda Creek. Sarah's left foot is on bedrock/sedimentary contact (Plate 1A).

Fill

Fill material between La Honda Creek and Highway 84 consists of riprap and soil-riprap mixtures. The riprap is usually composed of boulders of Mindego Basalt, but locally waste concrete is used. The basalt riprap is visually fresh to stained state and, based on a pit to dent quality (PQ-DQ) of the Schmidt rebound hammer test, has an estimated unconfined compressive strength of about 55 MPa (8,000 psi). Fill soil is silty clay to clayey silt (CL-MH) with angular, pebble to cobble-size clasts of underlying bedrock units. It is emplaced in 30 to 120 cm (11.8 – 47.2 in) lifts. Moist to saturated tor vane shear strength values range from 20 to 30 kPa (425 to 625 psf) (Appendix B).

### 3.4 SOILS IN THE LA HONDA WATERSHED

Three main soils occur adjacent to La Honda Creek: the Butano loam, Mindego clay loam, and Hugo-Josephine loams (Wagner and Nelson, 1954). All three are upland, residual (forming on bedrock) soils; their differing characteristics are based on parent material, slope, age and vegetation cover. The descriptions of these soils below are from Wagner and Nelson (1954):

Butano Loam

The Butano loam is a well drained to excessively drained soil formed on sedimentary rock, that lies on steep to very steep slopes ranging in elevation from near sea level to about 725 m (2380 ft) in elevation. The thickness ranges from 90 to 150 cm (35 – 59 in).

Mindego clay loam

The Mindego clay loam is a well drained to excessively drained soil formed on basic igneous rock. The soil occurs on steep to very steep slopes ranging from 300 to 600 m (785 – 1970 ft) in elevation. The soils are moderately deep.

Hugo-Josephine loam

The Hugo-Josephine loam is a well drained to excessively drained soil that formed on sedimentary rocks. Relief ranges from sloping to very steep. Elevation ranges from near sea level to 600 m (1970 ft). The normal depth ranges from 45 to 90 cm (17.7 – 35.4 in).

**Soil Qualities**

The soils in the La Honda watershed have differing engineering and ecological characteristics according to their composition. Based upon tests by Wieczorek (1982), the soils are mainly inorganic silty clays and clayey silts having medium to high plasticity. The soils are capable of absorbing large amounts of water, and are known for their slope-stability problems (Tables 3-1 and 3-2).

**Table 3-1.** Average engineering properties of soils derived from geologic units of the La Honda area. Data from Wieczorek (1982).

| Formation | Tahana Member, Purisima Formation | Mindego Basalt | Lambert Shale and San Lorenzo Formation |
|---|---|---|---|
| Lithology and Depth of Weathering | Very fine-grained sandstone and siltstone bedrock overlain by 5 m (16.4 ft) of soil and moderately weathered bedrock | Basaltic volcanic rocks (submarine flow breccia, pillow lava, and lithic tuff, overlain by 1.5 m (4.9 ft) soil and slightly weathered bedrock | Mudstone, siltstone, and shale bedrock overlain by 5 m (16.4 ft) soil and 9 m (29.5 ft) moderately weathered bedrock |
| Soil Characteristics | Inorganic clays and silts of medium to high plasticity (CL-CH, MH) with clay fraction of predominantly montmorillonite | Inorganic clayey silts of medium to high plasticity (ML to MH) with clay fraction of montmorillonite and illite | Inorganic clays and silts of medium to high plasticity (CH to MH) with clay fraction of montmorillonite and illite |
| Grain size (%) | | | |
| Gravel | 1 | 8 | 1 |
| Sand | 20 | 11 | 10 |
| Silt | 50 | 53 | 60 |
| Clay (<2 microns) | 30 | 28 | 29 |
| Plasticity | | | |
| Liquid limit | 51 | 50 | 55 |
| Plasticity index | 24 | 20 | 22 |
| Clay mineralogy (%) | | | |
| Montmorillonite | 90 | 67 | 65 |
| Illite | 4 | 28 | 30 |
| Kaolinite | 6 | 2 | 2 |
| Chlorite | 0 | 3 | 3 |

**Table 3-2.** Characteristics of soils adjacent to La Honda Creek. Data from San Mateo Area Soil Survey (Wagner and Nelson, 1954).

| Name | Depth (m) | Depth (inches) | Slope | Permeability (mm/hr) | Permeability (in/hr) | Rate of runoff | Erosion hazard | High water table | Water holding capacity | Workability |
|---|---|---|---|---|---|---|---|---|---|---|
| Butano Loam (BuF) | 0.5 – 1.5 | 20 to 60 | > $45^0$ | 20 to 64 | 0.80 to 2.50 | Very rapid | High | None | Low to good | Difficult |
| Mindego clay loam (MdF) | 0.5 – 1.5 | 20 to 60 | > $45^0$ | 1.3 to 20 | 0.05 to 0.80 | Very rapid | Very high | None | Good to High | Difficult |
| Hugo and Josephine Loam, steep (HuE) | 0.9 – 1.5 | 36 to 60 | 30 to $45^0$ | 5 to 64 | 0.20 to 2.50 | Rapid | High | None | Low to good | Difficult |
| Hugo-Josephine Loam, very deep, sloping (HvC) | >1.5 | >60 | 5 to $11^0$ | 5 to 64 | 0.20 to 2.50 | Slow | Slight | None | Good to high | Fairly easy |
| Hugo-Josephine loam, very deep, gently sloping (HvB) | >1.5 | >60 | 2 to $6^0$ | 5 to 64 | 0.20 to 2.50 | Very slow to slow | Slight | None | Good to high | Easy |
| Hugo-Josephine Loam, very steep (HuF) | 0.9 – 1.5 | 36 to 60 | > $45^0$ | 5 to 64 | 0.20 to 2.50 | Very Rapid | High | None | Low to Good | Difficult |

## 3.5 STRUCTURE AND SEISMICITY

Tectonic uplift controls the rates of erosion and stream downcutting, while even moderate earthquakes have triggered numerous landslides. A Richter local magnitude ($M_L$) = 6.1 earthquake whose epicenter was 53 km (33 mi) away, triggered a major landslide in the La Honda area in 1984 (see Section 3.6, Earthquakes).

The following discussion concentrates on seismically active faults in the region and possibly seismically active faults near La Honda. The study region is located between two seismically active faults, the San Andreas fault zone 8 km (5 mi) to the east and the San Gregorio fault zone 10 km (6.2 mi) to the west. More specifically, the study reach of La Honda Creek is bounded to the west by the La Honda fault, to the north by the Woodhaven fault and to the south by the Butano fault (Brabb and Olson, 1986). The following fault descriptions are mainly from Brabb and Olson (1986). Ages are given in millions of years (Ma) or years before present (BP).

### Faults

San Andreas Fault Zone

The San Andreas fault zone (SAF) is one of the most intensely studied geologic structures in the world. Large earthquakes having $M_L$ of 7 or more occurred on the fault in 1906, 1857, and 1838. Clahan and Wright (1994) working near Woodside in San Mateo

County, calculated an average annual slip rate of 20.5 ± 5 mm/yr (0.8 ± 0.2 in/yr) for the latest Holocene. They suggested that the San Francisco Peninsula segment of the SAF has an average recurrence interval of 130 ± 45 years for earthquakes comparable to the $M_L$> 7, 1906 earthquake.

San Gregorio Fault Zone

The San Gregorio fault is a segment of the right-lateral San Gregorio-Hosgri fault system which lies partly offshore. Near the town of San Gregorio, the San Gregorio fault consists of many individual strands forming a zone hundreds of meters wide, and influences the position of the modern day coastline (Clark, 1970 in Graham and Dickinson, 1978). Brabb and Olson (1986) concluded that the southern part of the San Gregorio fault in San Mateo County is seismically active, and Simpson and others (1997) concluded that the fault has accumulated sufficient strain to generate a magnitude 7-7.2 earthquake.

Weber and Cotton (1981) calculated that the average rate of right-lateral offset along the San Gregorio fault is between 7 to 11 mm/yr (0.28 – 0.43 in/yr) since the late Pleistocene (125,000 years BP). This rate is consistent with a slip rate of 9 mm/yr (0.35 in/yr) calculated by Graham and Dickinson (1978). Using long-term slip rates of 6 mm/yr (0.24 in/yr), 9 mm/yr (0.35 in/yr), and 11 mm/yr (0.43 in/yr), Weber and Cotton established recurrence intervals for large-magnitude earthquakes on the San Gregorio fault (Table 3-3):

**Table 3-3.** Recurrence intervals for large magnitude earthquakes on the San Gregorio fault From Cotton and Weber (1981); Weber (1994).

| Richter Magnitude | Recurrence Interval (years) if long-term slip rate (6 mm/yr or 0.24 in/yr) | Recurrence Interval (years) if long-term slip rate (9 mm/yr or 0.35 in/yr) | Recurrence Interval (years) if long-term slip rate (11 mm/yr or 0.43 in /yr) |
|---|---|---|---|
| 8.0 | 850 | 566 | 463 |
| 7.5 | 450 | 266 | 218 |
| 7.0 | 200 | 133 | 109 |

The maximum credible earthquake (MCE) for the San Gregorio fault is at least magnitude 7.6 – 7.7 and may be greater than 8. Weber and Cotton (1981) estimated the "most likely" recurrence interval for $M_L$ = 7.5 earthquakes along the San Gregorio fault zone to be between 300 – 325 years; Simpson etal (1997) concluded that the last surface event on the San Gregorio fault (estimated M=7) occurred between 733 and 228 years BP.

La Honda Fault

The La Honda fault extends from 1 km (0.62 mi) south of the town of La Honda northwest to Highway 92, a total distance of 26 km (16 mi), and is considered to be possibly seismically active. The fault trace is not exposed, but the fault is inferred from the truncation of several geologic units. Although the fault's dip has not been established, it is probably nearly vertical with a straight trace over varied topography and a deep earthquake hypocentral distribution. The apparent movement is scissors: west side down on the north and west side up on the south. Fault plane resolutions are not consistent with the regional stress field; but overall right-lateral motion is the most probable. Earthquakes associated with the fault are 7-7.9 km (4.4 – 4.9 mi) deep and $M_L$ = 2-3. The largest quake associated with the fault was a $M_L$ = 3-4, at a depth of 6-6.9 km (3.7 – 4.3 mi), located 2 km (1.24 mi) southwest of La Honda.

Woodhaven Fault

The Woodhaven fault passes 2 km (1.24 mi) north of the Weeks Creek and La Honda Creek confluence, trending northwest for 7 km (4.4 mi). A 1.5-km (0.9 mi) segment at the west end of the fault extends south along Borgess Creek were it probably joins the La Honda fault (Figure 3-1). Map relations suggest that the fault is a south-dipping thrust. The youngest rock unit cut by the fault is the Mindego Basalt of Oligocene to Miocene age (5.3 to 33.7 Ma), while the Purisma Formation of the late Miocene and Pliocene age (5.3 to 1.8 Ma) extends uncut across the fault, suggesting that the fault has not moved since late Miocene time.

Three clusters of earthquake epicenters could be associated with the Woodhaven fault. The first is located 4 km (2.5 mi) southeast of the fault and range from 1-12 km (0.6 – 7.5 mi) deep. Focal solutions for this concentration indicate a thrusting mechanism on a fault dipping 10 degrees southwest. Two concentrations of earthquake epicenters, one located at 7-10 km (4.4 – 6.3 mi) beneath the southeast end of the fault and the other northeast of the fault, could both be related to the Pilarcitos fault. The data do not conclusively show activity on the Woodhaven fault, but it is considered possibly, seismically active.

Butano Fault

The Butano fault extends 19 km (12 mi) southeast from Loma Mar to where it joins the San Andreas Fault zone near Laurel, Santa Clara County (Figure 2-1). The Butano fault is a high-angle reverse fault along the north flank of the Butano anticline, caused by the compressive forces that formed the anticline. The youngest rock unit cut by the Butano fault is the Tahana Member of the Purisma Formation of late Miocene to Pliocene age (5.3 to 1.8 Ma). Stream terraces of Pleistocene (1.8 Ma to 10,000 years BP) are not offset across the fault, suggesting that movement has not occurred on the fault since the Pleistocene. One fault plane solution near Portola State Park indicates left-lateral strike slip on a vertical fault plane. Earthquake activity near the southeast end of the fault zone indicates that the Butano fault is probably seismically active.

**Folds**

The regional structural trend of folds in the La Honda area is west/northwest. More specifically, the Weeks Creek syncline located 4 km (2.5 mi) north of La Honda, trends west, and is 4 km (2.5 mi) long. This syncline is part of a larger set of folds north of La Honda that vary in length from 1 to 4 km (0.6 – 2.5 mi), and trend west/northwest. The 4.5-km (2.8 mi) long Haskin Hill anticline is located 1.5 km (0.9 mi) south of La Honda and trends west/northwest. The La Honda anticline starts 3 km (1.9 mi) west of La Honda and trends west for 3 km (1.9 mi).

## 3.6 LANDSLIDES AND SLOPE EROSION

Landslides are the dominant natural geomorphic process in the La Honda Creek watershed and result in the loss of private and public assets. The depth and style of landslides depends, partly, on the underlying bedrock type and depth to bedrock. Materials most commonly involved in landslides in the La Honda area include the clay-rich residual soils that have developed on the Tertiary sedimentary rocks and volcanics of the Mindego Formation. Rainfall causes the main triggering mechanisms for landslides in the La Honda area: elevated pore water pressure and loss of cohesion. Regardless of moisture content, the soils in the La Honda Creek watershed are considered to be highly susceptible to earthquake-triggered mass wasting.

**Paleo Mega-landslides**

The present topography is inherited from paleo processes that were operative during a time when vegetation was more abundant and of a different type and rainfall was greater. Mega- landsliding carved the landscape especially in the areas closest to the streams where undercutting was most active and pore water pressure within the slide masses greatest. The mega-landslides cut through both volcanic and sedimentary bedrock. Based on their aspect ratio (length vs. width) and height of their scarps, most of these slides appear to have been (at least in their head areas) rotational slumps. The vegetation at the time would have structurally bound the loose soil mantle preventing shallow-seated (translational) mass wasting, but deep-seated mass rotational failures could still occur--especially in the clay-rich sedimentary bedrock units, or in the structurally incompetent members of the basalt--whenever the level of antecedent saturation precluded additional storm rainfall to drain.

Movement on these slides and subsequent mobilization of their masses formed thick deposits of colluvium that are exposed by modern, smaller, nested landslides (largely debris flows) throughout the watershed. Deposits of anomalously fine-grained sediment within the margins of the modern channel, such as downstream from Delay's bridge, indicate that periodic damming by landslide debris occurred.

**Transition to Present Processes**

Deforestation, change of land use to grazing, and then residential development combined with the overall drying climatic trend increased the amount of sediment eroded into the stream channel by surficial (as opposed to mass wasting) processes. The watershed reflects the transition stage between the older process of balancing large, sediment input due to mega-landsliding and the present overall degradation caused by reduced bedload delivered by smaller, more mobile, and less frequent debris flows.

Now that climate is less moist and deep-rooted vegetation less abundant, intense rainfall events trigger relative shallow debris flows in the clayey colluvium of the older slides. The small slides prevent triggering of the larger ones by: 1) reducing load at the head, 2) adding mass to the toe, and 3) relieving pore water pressure by intercepting groundwater within the slide mass.

**Gully Erosion**

Steep-sided gullies are forming in several locations, and regionally are a major problem, causing both loss of soil and fine sediment contamination in the watershed. These gullies appear to be a relatively recent (post-deforestation) feature because: 1) they are aggressively forming, cutting across relatively stable landforms, and 2) old, relict gullies do not appear prominently on aerial photographs as would be expected if they had been significant features at the time the mega-landslides formed.

**Recent and Active Landsliding**

During the intense storms of 1982 – 1983, a total of 18,000 debris flows occurred in ten Bay Area counties, with 4000 in San Mateo County (Ellen, 1989). Debris flows damaged at least 100 homes, killed 14 residents, and carried a 15$^{th}$ victim into a creek. The Love Creek slide in Santa Cruz County buried 10 people in their homes. Throughout the Bay Area, thousands of people vacated homes; communities were isolated due to road closures; and water, power, and telephone systems were disrupted. Preliminary estimates of total storm damage exceeded 280 million U.S. dollars with at least 66 million due to landslides and debris flows. Landslides accounted for 25 of 33 deaths attributed to the storm (Ellen, 1989).

Jayko et al. (1999) mapped landslides and debris flows in San Mateo County that were caused by the 1997-1998 El Niño storms. The authors found that earthflows, earth slumps and debris flows affected the rural areas west of State Highway 35 (Skyline Drive), with most triggered on February 2-3 between 11:30 pm and 12:30 am. The rainfall exceeded the debris flow threshold on the hillslopes causing three flows in the La Honda Creek watershed (one immediately adjacent to Highway 84 at Langley Creek, and two in the Woodhams Creek tributary basin). These flows occurred on slopes underlain by Pliocene and Pleistocene sandstone and siltstone of the Lambert Shale/San Lorenzo Formation. The authors state that although many hillslope failures occurred in the county, there were few reports of damage in the rural western part. However, the slides caused major road damage on State Highways 92 and 84 totaling an estimated 10 million dollars in repair costs (Jayko et al., 1999). Highway 84 was completely closed for 4 weeks following the storm, and a one-lane section is still present. The county estimated 8 to 12 million dollars of road damage (not including state highways) due to hillslope failures.

Wieczorek et al., (1989) discussed a landslide that occurred in December 1973, as part of a previously mapped, larger landslide complex, in the siltstone of the Tahana Member of the Purisima Formation. This slide destroyed two homes and cost the County of San Mateo $175,000 (1973 dollars) for road repair and stabilization.

**Material Susceptibility to Failure**

Brabb and Pampeyan (1972) and Brabb et al. (1972) showed the extent and distribution of landslide deposits in San Mateo County. A total of 29 major landslides occur adjacent to Highway 84 and La Honda Creek (not including tributaries). Brabb et al. (1972) ranked lithologic units in terms of the susceptibility and past record of failure. Although slope has a large effect, generally landslides deposits (colluvium) are most prone to failure, followed by the San Lorenzo Formation/Lambert Shale, the Tahana Member of the Purisima Formation, the Mindego Basalt, and the Monterey Shale (Tables 3-1 and 3-4).

Modern landslides tend to be steep debris flows that mobilize clayey colluvium within older landslides. The colluvium has fairly high shear strength when dry. But when saturated, shear strength decreases greatly. Cohesion is diminished as the solid becomes a "rheid"—a material that will flow under its own weight. Pore water pressure develops in the mass due to its low permeability thus reducing the normal stress which is relatively low on these steep banks, and the angle of internal friction can decrease by a factor of ten as the clay takes water into its structure. These relationships are expressed in Coulomb's equation:

$$\tau_{\phi} = c + (\sigma_n - \mu) \tan \phi$$

Where:
$\tau_{\phi}$ = Shear strength at failure
c= Cohesion
$\sigma_n$ = Normal stress
$\mu$ = Pore water pressure
$\phi$ = Angle of internal friction

**Table 3-4.** Landslide failure record for rock units, San Mateo County. From Brabb et al. (1972).

| Rock unit (Brabb et al. 1972) | Map symbol | Approx. area in county ($km^2$) | Approx. area in county ($mi^2$) | Approx. area that has failed ($km^2$) | Approx. area that has failed ($mi^2$) | Percent that has failed |
|---|---|---|---|---|---|---|
| Monterey Shale | Tm | 13.24 | 5.11 | 4.56 | 1.76 | 34 |
| Lambert Shale | Tls | 51.67 | 19.95 | 18.78 | 7.25 | 36 |
| Mindego Basalt | Tmb | 27.97 | 10.80 | 10.39 | 4.01 | 37 |
| Tahana Member of Purisima Formation | Tpt | 86.66 | 33.46 | 41.65 | 16.08 | 48 |
| San Lorenzo Formation/Lambert Shale,. | Tls | 17.69 | 6.83 | 11.81 | 4.56 | 67 |
| Landslide deposits | Qls | 212.25 | 83.88 | 217.25 | 83.88 | 100 |

Wieczorek (1982) mapped landslides in all units, except the alluvial fan deposits, and concluded that the type of bedrock and depth of weathering affected the depth and style of landslides. He noted that the Tahana Member of the Purisma Formation, the Lambert Shale and the San Lorenzo Formation weather extensively and deeply, up to 9.1 m (30 ft), forming highly plastic clay between weak corestones. Because of their cohesion and low shear strength, these units generate many slumps and earthflows, having slip surfaces in the residual soil or weathered bedrock. The Mindego Basalt weathers only within a few of the surface, typically 1.5 to 4.6 m (5 to 15 feet), hosting shallow debris slides and debris flows with slip planes at the contact between weathered rock and fresh rock. The soils produced from these units are also prone to landsliding (Table 3-5).

**Table 3-5.** Relationship between rock type, number, and styles of landslides. From Wieczorek (1982).

| Geologic Unit | Earthflow | Debris slide | Debris flow | Slump | Complex slump flow |
|---|---|---|---|---|---|
| Tahana Member, Purisima Formation | 13 (14%) | 11 (12%) | 4 (4%) | 51 (54%) | 15 (16%) |
| Lambert Shale/San Lorenzo Formation | 22 (33%) | 19 (29%) | 4 (6%) | 17 (26%) | 4 (6%) |
| Mindego Basalt | 12 (17%) | 27 (39%) | 19 (27%) | 9 (13%) | 3 (4%) |

Wieczorek (1984) mapped over 230 landslides in a 13 $km^2$ (5 $mi^2$) area near La Honda, at a scale of 1:4,800. He identified location, direction of movement, state of activity, certainty of identification, dominant movement type, maximum depth of failure surface, and the date of known movement. More than half of the recently active landslides are reactivated parts of recently active or questionable dormant landslides. Definite dormant and probable dormant landslides show the lowest incidence of reactivation, suggesting that they may have achieved long-term stability (Wieczorek, 1982).

## Triggering Mechanisms

Rainfall

Accumulated seasonal rainfall, storm intensity and duration all affect the initiation of landslides. Wieczorek (1981) found that water year total precipitation affected the number of landslides in the La Honda area. He reported ground water levels and precipitation for the La Honda area between July 1975 and June 1980. Precipitation was measured using a recording rain gage, bucket gages, and local NOAA-operated gages. Annual water year and landslide totals are summarized below in Table 3-6.

**Table 3-6.** Water year (WY) total precipitation and number of landslides per year, La Honda area. From Wieczorek (1982).

| | WY 1976 | WY 1977 | WY 1978 | WY 1979 | WY 1980 | WY 1981 |
|---|---|---|---|---|---|---|
| **Water Year Total (mm)** | 339.6 | 358.7 | 990.4 | 662.2 | 808.0 | 571.5 |
| **Water year total (inches)** | 13.37 | 14.12 | 38.99 | 26.07 | 31.81 | 22.5 |
| **Number of active landslides [a]** | 0 | 0 | 20 | 1 | 14 | 2 |

Wieczorek (1984, 1987) found that landslides were triggered by high-intensity, short-duration storms that caused rapid saturation near the ground surface, and by gradual saturation due to rising groundwater. Short-duration, high-intensity storms tend to cause debris slides and debris flows, whereas a series of long-duration storms tend to cause slumps and earthflows.

**Figure 3-5.** Desperate measures used in an attempt to reduce infiltration into the "Blue tarp landslide" (Plate 1A).

Wieczorek (1984) measured changes in ground water levels in response to rainfall intensity and duration. He found that the rate and magnitude of ground water response to precipitation depended on previous cumulative seasonal rainfall; storm duration and storm magnitude; perched aquifers associated with the shear zones of previous landslides; topographic position of the piezometers; and slope. Wieczorek (1987) analyzed rainfall records between 1975 and 1984 and determined the antecedent conditions and the levels of continuous, high-intensity rainfall necessary for the initiation of debris flows. He found that antecedent rainfall totaling at least 280 mm (11 in) is necessary for debris flow initiation, with rainfall occurring in the previous 7-to-30 days having the largest effect.

The debris flows were either rotational or translational soil slides and were classified into three categories: deep slumps, shallow slumps and slides, and very shallow slides over bedrock. Deep slumps are typically 1 to 3 m (3.3 – 9.8 ft) deep; are not associated with gully erosion or undercutting by streams; form on concave slopes between 20 and 28°; and are likely initiated by converging throughflow creating high pore-water pressures. Shallow slumps and slides are 0.3 to 1.0 m (1.0 – 3.3 ft) deep, occur in soils on planar to concave hillslopes 24 to 40 degrees, and commonly occur in areas of older sliding. Very shallow slides over bedrock are 0.2 to 0.5 m (0.7 – 1.6 ft) deep, occur on slopes between 26 and 47 degrees, and have a permeability barrier between the upper soil and the lower, well-cemented bedrock. Wieczorek concluded that long duration, moderate-intensity storms predominately triggered deep slumps, whereas short-duration, high-intensity storms triggered very shallow slides over bedrock (soil mantle delamination).

Wilson and Wieczorek (1995) developed the "leaky-barrel" model relating rainfall intensity and duration, and subsequent changes in pore water pressure, to the initiation of debris flows. The model predicts debris flow response to rainfall duration and intensity using antecedent rainfall, effective porosity, critical amount of retained rainfall, and the accumulation of infiltrated rainfall in the zone of saturation. The authors analyzed storm events that did or that did not initiate debris flows using historical rainfall records and groundwater levels. They calculated a new rainfall-intensity/duration threshold for the initiation of debris flows. The model predicts that antecedent rainfall greater than 280 mm (11 in), with 8.5 mm (0.33 in) of retained rainfall in the slope can trigger debris flows. The threshold is higher than the curve created by Wieczorek (1987), but lower than the regional San Francisco Bay area curve created by Cannon and Ellen (1985). Wilson and Wieczorek concluded that slopes most susceptible to debris flows in the La Honda area are well drained but highly sensitive to fluctuations in pore water pressure.

Earthquakes

Earthquakes have triggered several landslides in the La Honda watershed. Regardless of soil moisture, soils in the La Honda are considered highly susceptible to landsliding. The 1989 M=7.1 Loma Prieta earthquake was the most recent large event to affect the region; it produced a modified Mercalli intensity (MMI) =VII throughout the La Honda watershed (Plafker and Galloway, 1989). Thompson and Evernden (1986) predicted Mercalli intensities of VII throughout most of the watershed, and IX along the channel due to an earthquake on the San Andreas fault similar to that of the M=8.2-8.3 San Francisco event.

Wieczorek and Keefer (1984) described a landslide in the La Honda area that was triggered by the Morgan Hill, CA earthquake of April 24, 1984. The landslide was 53 km (33 mi) from the epicenter of the earthquake, which had a Richter surface magnitude ($M_s$) = 6.1, one of the furthest distances recorded worldwide for an earthquake of that magnitude. The strong-motion instrument nearest to the slide, 10 km (6.2 mi) to the east at Stanford University's Linear Accelerator Center (SLAC) Test Laboratory, recorded a maximum acceleration of 0.032g. Ground response in the La Honda area suggested a MMI of V to VI. La Honda had received below-normal seasonal rainfall before the event therefore, Wieczorek and Keefer suggested that unusual conditions such as focusing of seismic energy at the site, anomalous perturbations of the ground-water level by shaking, or a marginal stability of the hillside before shaking began likely triggered the landslide.

The Weeks Creek landslide is at least 3,400 years old based upon pollen records (Wilson and Wieczorek, 1995). It experienced one meter (0.3 ft) of downslope movement during the 1906 San Francisco earthquake, and is currently intermittently active. Continued movement of the slide has disturbed the roadbed along lateral scarps that cross Highway 84 at the Christmas tree farm located 1 km north (0.6 mi) of the study reach.

## 3.7 FLUVIAL GEOMORPHOLOGY

### General Statement

This section describes the main processes operating in the La Honda Creek channel. Details regarding the channel, slope, cross-sections, substrate materials, and bottom pertinent to salmonid habitat are presented in Section 6.

La Honda Creek is a perennial, third-order channel flowing through a tectonically active landscape marked by many small faults and folds. In addition to the channel having to maintain equilibrium with the continued regional uplift, it must also transport the water and sediment delivered from land use and landslides.

Each of the four named and smaller, unnamed tributaries to La Honda Creek has a unique confluence style; this affects the amount and timing of water and sediment supplied to the mainstem creek. Woodruff and Weeks Creeks are at grade with the main stem creek, Langley Creek enters through a large-diameter (2 m or 6.6 ft) metal culvert, while Woodhams Creek is above grade, forming a hanging tributary (Figure 3-6).

La Honda Creek mainly flows directly on bedrock or over a veneer of gravel, but in some reaches, it has an alluvial substrate. Its Rosgen classification ranges from 1A to 3B (Rosgen, 1996). Because of this variation, the channel morphology, sediment size distributions, and sediment routing do not follow patterns typical of purely alluvial channels. For example, the channel in reach 3B (Figure 6-3) is incised approximately 2 m (6.6 ft) with nearly vertical banks, and has a very flat bed, giving a trapezoidal cross-section. This unusual channel geometry is likely due to the many bedrock reaches in this segment and the style of landslides on the adjacent hillslopes.

Landslides are the dominant source of sediment in the channel, ranging from boulders to "fines". Winnowing of this material produces gravels whose size makes them appropriate for salmonid spawning. These gravels are probably best and most abundant in the year immediately following a landslide event, before the sediment becomes embedded, and channel armor has developed. Although some of the channel patterns are due to bedrock outcrops, others are caused by debris flows entering the channel. The debris is a highly viscous mixture that leaves a thick package of sediment when it finally comes to rest. A landslide mass may form a temporary dam that backs up water and collects fine, suspended sediment such as the bedded silt unit described above.

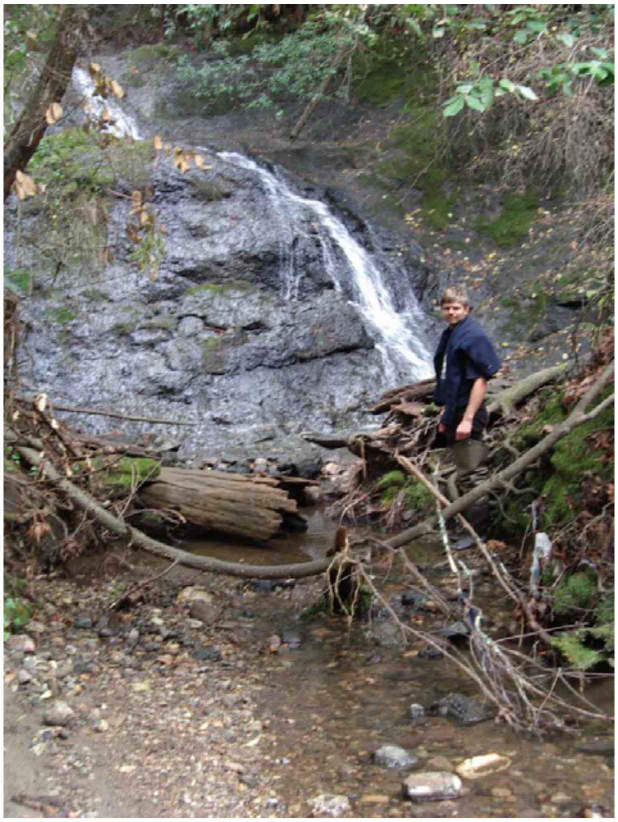

**Figure 3-6.** Hanging tributary at Woodhams Creek (Plate 1A).


**Figure 3-7.** View upstream of sediment body winnowed from debris flow entering channel temporarily producing braided pattern. Landslide scar seen at upper end of photo. In time, the creek breeches the dam, returning to its original gradient. Reach 2B (Figure 6-3) appears to be affected by this process: the bankfull channel width is much wider compared to up and downstream, and remnants of landslide material are visible in many locations.

Localized landslides also have a significant influence on the bed elevation. Initially, the stream forms a temporary, braided pattern. As fines are winnowed, the freed granular sediment moves in pulses downstream, progressively filling pools and forming bars. This process occurs over several years: a pool can fill with sediment in a single year, and remain filled for a couple of years until a flow event scours the pool, moving the sediment down stream where it may deposit in another pool.

**Bank Erosion**

Bank erosion in La Honda Creek destabilizes the banks and releases fine sediment that may be detrimental to salmonids. The erosion rates estimated herein compare the relative age and magnitude of bank erosion within each sample reach and thus, allow the relative threat to Highway 84 and other property adjacent to the banks (Figure 3-12) to be assessed.

Bank erosion, or scour, occurs where stream energy is directed laterally onto the bank, such as on the outside corner of meanders or adjacent to LWD, and in areas where channel gradient is elevated due to underlying resistant bedrock or to sediment deposits that raise the bed elevation. Scour also occurs in areas of weak bank material, in areas having little or no bank vegetation, or in areas affected by poorly planned or constructed revetment (Figure 3-8). Bank erosion can also result from regional uplift and tectonic activity: as the landscape is uplifted, channels erosionally incise to maintain their gradient. Landslides also accelerate bank erosion. If the landslide mass fails directly into the channel, erosion of the toe of the landslide will occur, as well as potential erosion on the opposite bank due to altered channel configuration.

The extent of bank erosion along each bank was recorded for the entire length (25 bankfull widths) of selected sample reaches (Figure 6-3) as indicated by exposed roots of trees or overhanging vegetation, or by undercut bank, revetments, bridge pilings, or other structures. Two measurements were made: 1) average distance of retreat, and 2) average height over which erosion was evident. Multiplying these values with the length of eroding bank gave an average volume of erosion and sediment released. The rate of erosion was approximated based on the estimated of age natural features, such as tree roots, and the estimated age of undercut feature.

A total volume of 7130 $m^3$ (9,330 $yd^3$) of bank loss was measured in the seven sample reaches (Figure 3-9). The greatest volume occurred in reach 2B (4,673 $m^3$ or 6,116$yd^3$), followed by reach 3A (745 $m^3$ or 975 $yd^3$). Combined, these two reaches represent 76% of all bank erosion measured. The average volume of bank erosion per unit channel length was also calculated (Figure 3-10). The maximum amount occurs in reach 2B, with 21 $m^3$ (28 $yd^3$)of erosion per meter of channel length. This value is unusually large though, because it includes the landslide there.

**Figure 3-8.** Failing portion on the downstream end of sackrete bank revetment, 790 m (864 yd) downstream of Weeks Creek (Plate 1B). Flow from left to right.

Erosion rates varied between a few centimeters per year to 20 cm/yr (7.9 in/yr). The highest rates appear to have occurred in the last 10-20 years and probably reflect the combined affects of the storms of 1982, 1883, 1995, and 1997 and other smaller storms in between (Figure 3-11). The method used to calculate rates is not sensitive to erosion due to individual storms, yet this is undoubtedly when the most occurs.

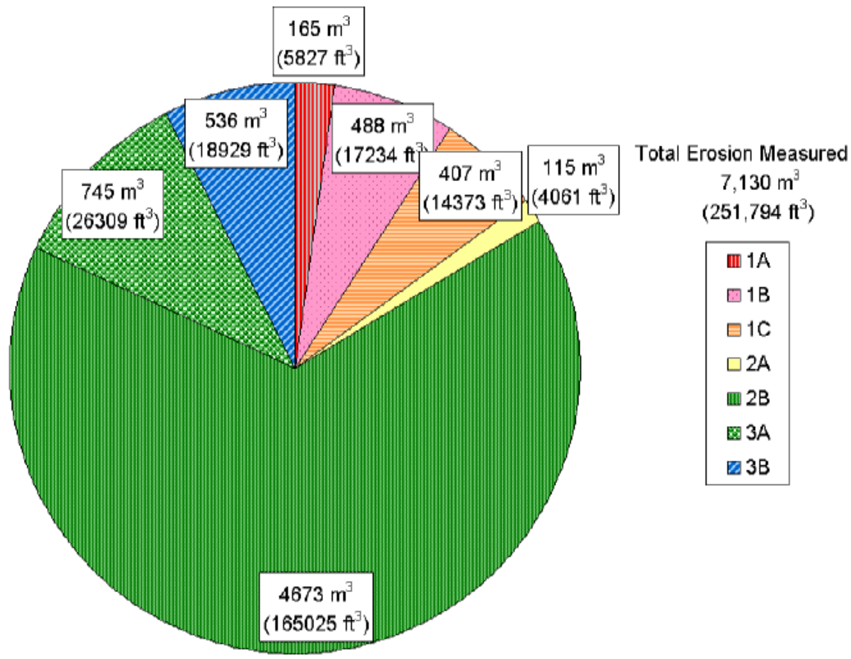


**Figure 3-9.** Total volume of measured bank erosion (m$^3$) in each sample reach.

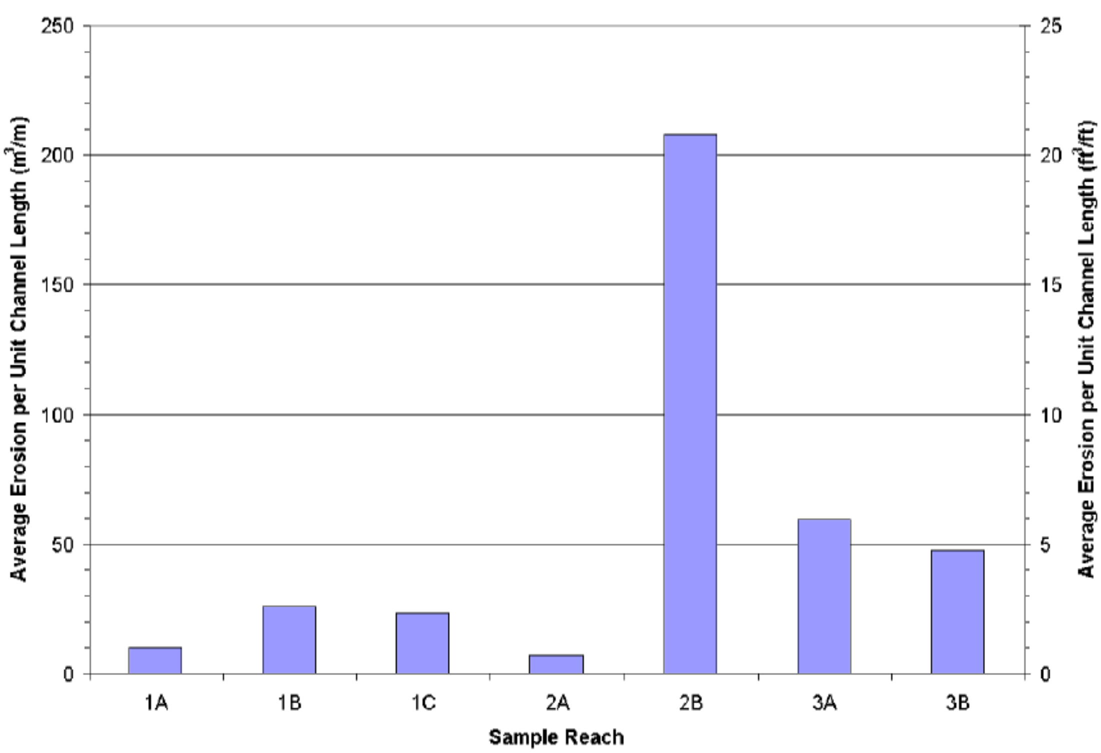


**Figure 3-10.** Average bank erosion per unit channel length in each sample reach.

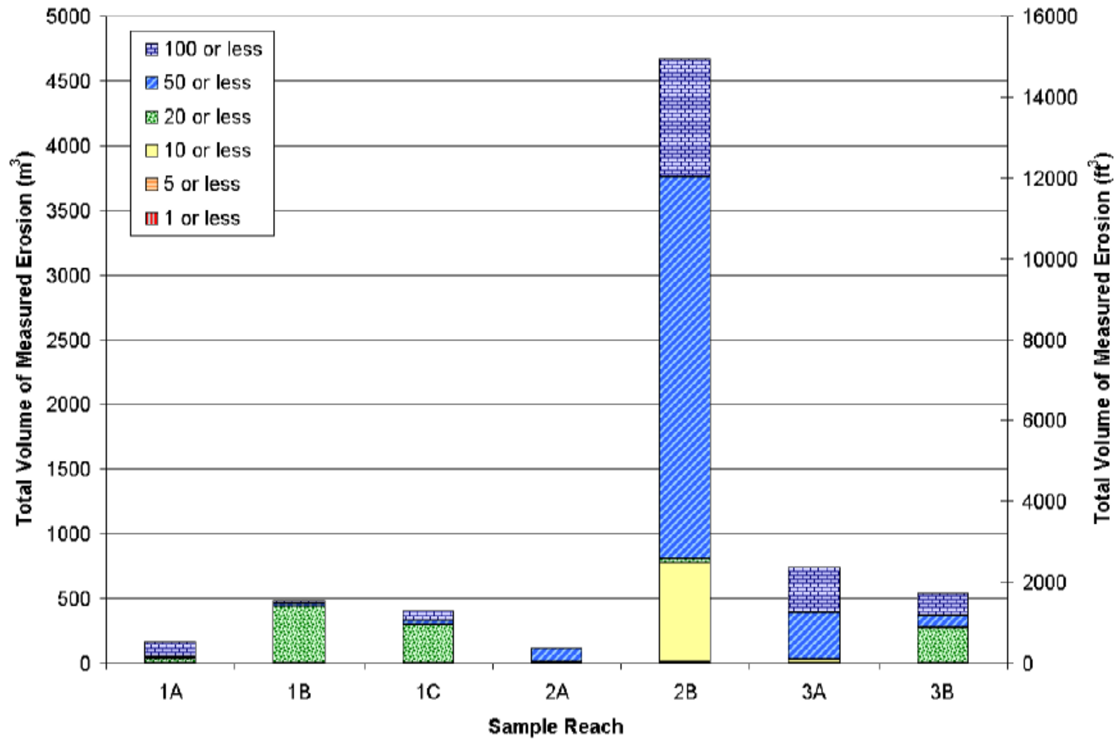


**Figure 3-11**. Age estimates (years)associated with measured erosion in each sample reach.

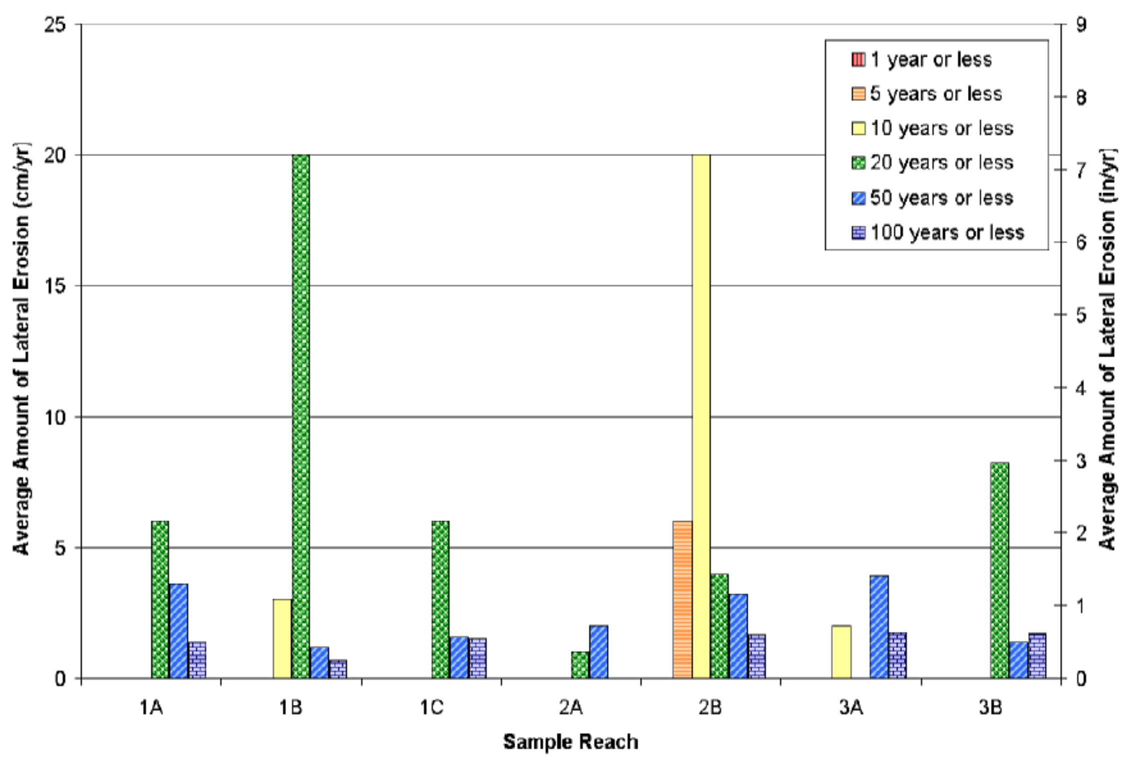


**Figure 3-12**. Average rate of lateral bank erosion (cm/yr) in each sample reach.

**Knickpoints**

Knickpoints are locations where the gradient of the thalweg abruptly changes. Knickpoints are notable in several places in the channel, particularly between Langley and Weeks Creeks (Plates 1A,B). These appear to be recent features and are probably a response to the 1997-8 El Niño floods. All are situated upstream from meanders wherein large bars containing cobbles winnowed from landslides, have been deposited mid-channel and to the outside of the meander (Figure 3-13). In some cases there is still a relict channel (now abandoned) on the outside, but in others, there is a pond. The bar has forced the low flow to the inside of the meander, shortening the channel length. This may conceivably have increased the gradient enough to initiate knickpoint migration.

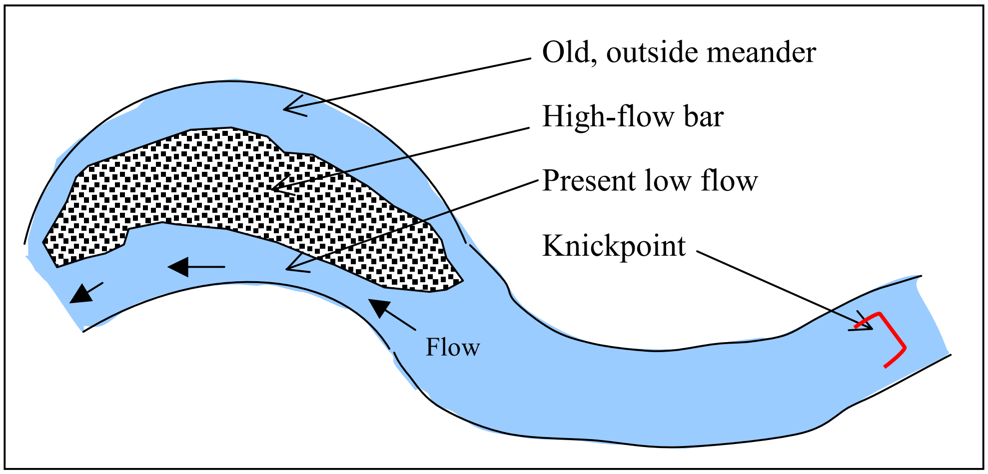


**Figure 3-13.** Schematic diagram showing relationship between knickpoints and channel features, 280 m (919 ft) downstream of confluence with Woodruff Creek (Plate 1B).

**Aggradation vs. Degradation of the La Honda Creek Channel**

Although areas in the La Honda Creek channel undergoing aggradation (deposition) the preponderance of evidence indicates that overall, the channel is down cutting:

1) Most of the engineered structures in the channel, such as the concrete footer at the Trailer Park bridge, the gabion wall downstream from Apple Jack's, or the concrete wall on the south side of the town of La Honda are being undermined or otherwise damaged by erosion (Plate 1C, Figure 3-14). The gabion wall shows two generations of repair, each more extensive (Figure 3-15). The latest was emplaced because of down cutting at its base. Damages are probably due to flows later than the 1997 event because the wire shows little wear, denting, or distress as it would have had if it been there during the 1997 event.

2) Most of the larger pools have been scoured into bedrock rather than into alluvium.

3) Upstream of Memory Lane 80 m (262 ft), (Plate 1C) are the remains of an old, concrete check dam that is now broken to streambed level; the left 4 m (13 ft) are exposed while on the right end, 1.5 to 2 m (4.9 to 6.6 ft) are buried beneath gravel. The left abutment extends 2 m (6.6 ft) above the channel floor; the downward extent is not known. The dam presently acts as an inadvertent grade control structure. On the crossover reaches upstream

and downstream are knickpoints approximately 30 cm (1 ft) high. If the channel were aggrading, this feature would have been buried by now.

4) Most of the cohesive banks are undercut, some as much as 2.2 m (7.2 ft).

5) The $D_{50}$ of many gravel bars is greater than expected high flows could move, indicating that these coarse clasts are a "lag" deposit left behind by scouring during high flows (Figure 3-16).

6) Sand on the channel bottom seems to be unevenly distributed and consistent with pulses that work their way downstream rather than forming semi-permanent bars. Sand drapes deposited over gravel bars indicate that sand deposition is related to near-bankfull flows, but velocities were too low to move gravel on the bars.

7) The present distribution and type of sediment are largely the result of the stream cutting through deposits laid down during the 1997 event. During this event, gravel bars extended across the creek and have since been eroded by lower flow events. Gravel bars have steep margins on their streamward sides due to subsequent scour. The imbrication direction inside these bars is consistent with direct downstream transport rather than complex, lower-flow braiding.

The predominant degradation occurring within the channel indicates that further bank erosion will occur, and that attempts to protect the banks must be done with full understanding of the site's operative processes lest bed or bank erosion be exacerbated downstream.

**Figure 3-14.** Downstream end of concrete wall in the town of La Honda (Plate 1C). Arrow indicates flow direction. Sarah points to the former grade level at the time the wall was constructed. The footing is now undermined 0.75-1 m (2.5 – 3.3 ft) by down cutting. Accelerated bank erosion is also evident at the end of the wall. Attempt at bioengineered repair at stream level.

**Figure 3-15.** Gabion wall undermined by erosion. Arrow indicates flow direction. Downstream (right) end and base have been extensively repaired (Plate 1C).


**Figure 3-16.** Oversized clasts in gravel bar at the confluence of Weeks Creek (Plate 1A). Arrow indicates flow direction. Note steepened lower banks due to downcutting.