Marine Disposal of Landslide Debris along Highway One: Environmental Risk Assessment and Monitoring Protocols

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Photo: McWay Landslide - October 1983

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1. Purpose

State Highway One crosses many cliffs and bluffs that are subject to periodic landslides causing road closures and continual maintenance problems. Highway maintenance often involves moving landslide debris from the road and disposal in the adjacent marine environment, the natural sink for slide material if the highway were not present. Maintenance activities often deviate considerably from the natural patterns of slide movement and sediment dispersion in marine systems. Disposal of landslide debris effects marine habitats and biological communities by direct burial, by sand scour, and by plumes of fine suspended sediment. These are also natural processes impacting marine habitats and communities.

The purpose of this report is to determine which highway activities have the greatest ecological impacts on the marine environment, how these might be reduced or avoided, and what environmental conditions should be monitored if impacts are likely to be ecologically significant. Monitoring recommendations are based (in order of importance) on the likelihood of significant ecological impacts, the ability to assess these impacts at the local landslide setting, and additional applied science that can be done at the site and will improve disposal operations along the entire coast.

2. Background

Coastal landslides often move into the nearshore marine environment and impact plant and animal communities along the shore. These slides commonly occur along the coast of central and northern California, where unstable sedimentary deposits are prone to slumping from steep coastal bluffs or cliffs (Figure 1). The largest slides often are triggered by heavy rainfall and earthquakes. But there are also slides that are steep, highly active, and continually forming erodable beaches at the toe, such as Waddell Bluffs. The bases of other slides, often older, become armored with large boulders impeding beach formation and erosion.

Most of the central and northern coast of California is fringed by State Highway One, a major scenic highway as well as access to many small coastal communities. The highway cuts through dozens of active landslides, old slides, and areas of potential sliding. During years of heavy rainfall or after earthquakes, many coastal landslides bury the road with debris or otherwise damage it. Slide debris must be removed and often is deposited into the adjacent nearshore marine environment. Some active landslides require regular maintenance to remove slide material and keep the highway open. This material also is dumped into the adjacent marine environment. Movement of landslide debris into the marine environment is a frequent and widespread natural phenomenon along the California coast. Although the highway interrupts and modifies this natural movement, the adjacent marine environment is the natural sink and therefore usually the best disposal site for landslide debris deposited on the highway.

The Moss Landing Marine Laboratories has been exploring the ecological impacts of the marine disposal of landslide debris from Highway One at three primary locations during the last decade: McWay Rocks, along the Big Sur coast, Waddell Bluffs, between Santa Cruz and San Francisco, and Lone Tree Creek, along the coast north of San Francisco. The primary ecological impacts of debris disposal come from direct burial of habitats and communities, sand scour, and turbidity. Intertidal habitats and communities are most susceptible to direct burial from landslides. Plants and animals living in both intertidal and subtidal communities are subject to greater disturbance from sand scour caused by the movement of coarse, poorly consolidated sediments by strong wave action. Sand scour probably effects the largest area of marine habitat. Subtidal plant communities and to a lesser degree marine animals are impacted by increased turbidity and deposition of fine suspended sediments.

The ecological impacts of dumping landslide debris into the marine environment are strongly influenced by natural patterns of sediment disturbance, the quantity of introduced sediment, and the deviation of dumping practices from natural patterns of sediment movement and deposition into the marine environment. The most useful natural history for predicting these impacts is the severity of natural disturbances to the sedimentary environment of a particular locale. For example, Waddell beaches are highly disturbed by natural patterns of sediment burial, which the native plants and animals survive. Disposal of landslide debris here has no detectable ecological impacts compared to the natural patterns of disturbance (Bretz 1995). Highway maintenance at McWay Rocks (Figures 2-3) and Lone Tree Creek (Figures 4-5) have much greater impacts on the marine environment than highway activities at Waddell Bluffs. These massive slide manipulations are much less like the natural movement of slide material than are highway activities at Waddell Bluffs. The manipulated slides may be more like extreme natural landslides occurring at infrequent intervals of 100 to 1000 years. Lone Tree is highly disturbed by naturally turbid waters and sand movement and inhabited by communities that tolerate and thrive under these conditions. As a result, disposal of landslide debris only had significant ecological impacts related to direct burial of marine habitats and communities (Moss Landing Marine Laboratories 1996). McWay Rocks, in contrast, is the least disturbed by natural inputs of sediment from landslides and other sources. The biological communities here show the greatest changes related to disposal of landslide debris (Burdett 1992, Kiest 1993, Kim et al. 1998). These impacts are outlined in greater detail in the Appendix.

3. Marine Disposal Operations

Marine lab staff have visited all major marine disposal areas from Highway One along the northern and central California coast with Caltrans engineers, environmental planning managers, and highway maintenance staff. Disposal operations along the Big Sur coast (Figure 1) are representative of the larger coastal region and can be divided into several types:

- Disposal after catastrophic landslides
- Disposal from continuous cliff slides
- Disposal on creeping landslides
- Disposal after episodic small slides, rock falls, and other highway activities

Disposal operations after catastrophic landslides (Figures 2-5) have significant ecological impacts to the marine environment: all other disposal operations are done with no ecologically significant impacts to the marine environment.

3.1 Disposal after catastrophic landslides

The two largest catastrophic landslides that closed Highway One along the central and northern coasts were at McWay Rocks and Lone Tree Creek (Figures 2-5). In each, large volumes of soil were excavated from the east side of the highway and disposed on the west side in a large fill. The fill extended into the adjacent marine environment and buried underlying habitat. Rain eroded the entire fill and waves eroded the toe. Eroded sediment entered the local marine environment and was dispersed in suspended plumes and along the bottom. A number of potential future catastrophic landslides also have been located along the highway (e.g., Figure 6).

Ecological Evaluation

Marine impacts were much less at Lone Tree Creek compared to McWay Rocks because the slide was smaller, the nearshore environment naturally was more disturbed by sediment and there was more armoring of the slide toe by large boulders (Figures 4-5). Boulders were present in the slide material and large rocks were placed at the toe during construction to help retard wave erosion. Highly turbid water is common along the Lone Tree coast. Continuous sediment inputs come from eroding cliffs, San Francisco Bay, and local lagoons and other drainages. Sediments have high silt, clay particles as well as large boulders. At Lone Tree, underwater visibility under the best conditions is rarely more than one meter. As a result, light loving kelps are absent and algal communities are poorly developed. In addition, the fringing rock reefs rarely extend beyond a water depth of 10 meters and are still well within the influence of heavy waves and intense sand scouring. Consequently the only ecologically significant and detectable impacts of the landslide were caused by direct burial of intertidal and shallow subtidal habitats and by the unstable rocky habitats that developed at the slide toe.

McWay Rocks are part of an underwater reserve in Pffeifer-Burns State Park. On good days, underwater visibility is 20-30 meters. The worst day of water clarity is better than the best day at Lone Tree. Kelp forests are extensive and harbor rich algal communities. The fringing coastal rocks often extend to water depths of 20-30 meters where the impacts of wave action and sediment movement are much less than at Lone Tree. The McWay slide material is a relatively coarse sand with few large boulders. The massive slide buried a much larger area of intertidal and shallow subtidal habitat than the Lone Tree slide. The sediment plume reduced the cover of algal communities in the adjacent kelp forests, but sand scour impacted rocky communities over the largest habitat area. A layer of coarse fill sand moved over the finer sand deposit to water depths greater than 30 meters and almost a kilometer to the south.

Past monitoring indicates that covering and stabilizing the slide with native vegetation reduces sediment erosion from the fill and into the marine environment and consequently reduces the impacts to the ecological communities. At McWay, the slide fill was not planted with native vegetation and only the top of the fill was planted at Lone Tree. If the fill material had been covered with native plants, there would have been a significant reduction of impacts to the marine environment at both sites.

Any exposed, unvegetated soil that is created by construction and maintenance activities along the highway (Figures 7-8) should quickly be covered with native plants. This is essential for catastrophic landslides because they have the most significant impacts to the marine environment. In addition, it is imperative that drainage water from the landslide not be drained into or over the fill: it should be drained to one side of the slide like the present drainage at McWay. Exposed soils with high water content should be planted with willow trees for maximum erosion control. Protocols for planting steep landslide faces are being developed at the McWay site.

Monitoring

Both catastrophic landslides required monitoring programs to document sediment movement into and through the marine environment and the ecological impacts of sedimentation from highway disposal activities. The Lone Tree slide was monitored for six years including a year of baseline work before the fill was deposited and five years of post-disposal monitoring. Continued monitoring was recommended for two critical processes: sediment movement from the slide face and beach and colonization of rocky intertidal communities. No significant ecological impacts were documented in the subtidal environment beyond the slide toe.

The McWay slide was monitored for 10 years, but the monitoring started three years after the deposition of fill and no monitoring was done during a two year gap. This is the final year of the 10 year program. Continued monitoring is recommended for sediment movement from the slide face and beach and for the nearshore plume of suspended sediments. The are no rocky intertidal communities like those present at Lone Tree. Although there are significant ecological impacts to the subtidal environment, these can be monitored less frequently, perhaps after another five years, to document the predicted spread of slide material and the eventual exposure and colonization of pinnacles and other rock reefs. Unlike Lone Tree, the slide fill extended well into the McWay Rocks subtidal and buried rocky reefs and the lower portions of large nearshore pinnacles. Although there has been considerable transport of slide sediment through the subtidal environment, the rocky habitats are not likely to be exposed again until large storm waves erode the deeper burial deposits. When this occurs, the exposed rocks will be recolonized by marine animals and plants. If the slide face can be stablized with native plants, surface erosion should be dramatically reduced and the plume of suspended sediments into the nearshore should also be reduced around the slide.

The past monitoring programs at the two catastrophic sites established general criteria for monitoring potential impacts to the marine environment. First, and most importantly, is to ***conduct a field trip*** to the site with scientists who work on these processes and Caltrans staff including environmental managers, engineers, and local maintenance crew. Each site is unique and may require significant variations from the general monitoring outline. On this field trip, the group will assess the specific monitoring requirements of a site using the following outline as a general guide.

Sediment Transport (in order of importance)

• Bathymetric Maps are necessary for the pre-manipulation engineering designs of the erodable buttress and as a baseline for measuring potential impacts from the slide. The bathymetric map is also useful for planning any subtidal biological surveys, and re-locating sampling sites. Bathymetric and sidescan surveys, along with aerial photography for topographic mapping, should be the first tasks completed in a slide investigation.

• Sidescan Sonar Maps show the burial of subtidal habitat and the seaward extent of the toe of the slide fill. This is useful for management evaluations of the area of severely impacted marine habitat, and secondarily to link the physical disturbance with ecological changes in nearshore communities. Sidescan surveys also provide detailed maps of the nearshore sedimentary habitats around the slide as a baseline for measuring potential impacts.

• Cliff Erosion measurements are essential physical information for management and general scientific merit. The erosion of the slide fill provides the most useful information on the total input of sediment to the marine environment as well as temporal variations in this input. This monitoring also provides information on the stability of the fill and the mechanisms of erosion. It is also the most important indicator of potential ecological impacts.

• Beach Erosion and Accretion measurements provide basic management information on the area of buried intertidal habitat, and essential scientific information for assessing the ecological impacts to intertidal communities.

• Sediment Plume measurements provide information on the spread of suspended sediment into the nearshore environment and how this movement varies as the slide ages. They can also verify current information from the region, such as general longshore transport and the structure of coastal eddies. The plume measurements are the best indicator of the direction and minimum extent of nearshore sediment movement. Plume studies are particularly useful in clearer water, such as around Big Sur, where the biological communities are less adapted to turbid water.

• Bedload Transport measurements are usually not useful if disposal is into a complex rocky and clastic sedimentary environment like the type which borders most potential sites of catastrophic landslides. These habitats are too geologically complex for investigating bottom sediment movement with in situ instrumentation- mostly because there are numerous rock reefs which interrupt longshore sediment transport. Bedload transport studies can be extremely useful in less complex environments, farther offshore, or when tracking much larger sediment sources (rivers). If a slide deposit has a unique mineralogical signature, then slide sediment could be tracked using mineralogy.

Ecological Impacts

• Intertidal Communities should be monitored before and after the slide fill is deposited. This will determine the area of habitat that is directly buried by the toe, impacts to adjacent habitat, and development of new habitats and communities as the slide toe erodes and stabilizes. The need for monitoring intertidal and subtidal communities varies from site to site. The intertidal monitoring was not important at McWay, and subtidal monitoring was not important at Lone Tree.

• Subtidal Communities should be monitored before and after the slide fill is deposited. This will determine the area of habitat that is directly buried by the slide, impacts to adjacent habitat, and development of new habitats and communities as the slide toe erodes and stabilizes.

3.2 Disposal from continuous cliff slides

Waddell Bluffs is the best example of sediment disposal from a cliff landslide where sediment continuously erodes from the upper slide onto the highway, and is moved to the seaward side of the highway for disposal down slope at the appropriate time of year. Waddell Bluffs is one of the largest continuous cliff slides along the coast, and the slide toe is at the top of an extensive rocky intertidal shale bench. This habitat harbors a rich animal and plant community well adapted to extreme seasonal episodes of sand burial. Most continuous cliff slides along the Big Sur and many other coasts end in narrow boulder beaches containing extremely sparse rocky intertidal communities or benthic infaunal assemblages. Therefore, Waddell Bluffs is likely to be one of the most sensitive marine environments adjacent to a continuous cliff landslide. If significant ecological impacts are not detected here, they are less likely at most if not all other comparable landslide settings.

Ecological Evaluation
Highway activities at Waddell Bluffs have the least disruptive ecological impacts to the marine environment compared to McWay Rocks or Lone Tree Creek; and primarily involve direct burial of habitats. Here road maintenance activities are most like natural patterns of slide movement and deposition. The slide is very active with more or less continual movement of sediment down the face and onto the upper beach. The road interferes with the natural sedimentary patterns requiring excavation of slide material from the east side of the road and stockpiling on the west. Each winter the stockpiled material is pushed on to the lower slide face (west of the road) and thus on to the beach below. Disposal occurs in the winter when natural movement of sand is highest. Animal presence is lowest on the winter beach. The natural seasonal movements of sand on and off the beach and on and off the shale benches have such dramatic impacts on intertidal communities that the ecological effects of dumping slide material from the highway could not be detected (Bretz 1995, Moss Landing Marine Laboratories 1996), and no additional monitoring is recommended here.

Monitoring
Since most if not all other examples of marine disposal from continuous cliff slides are likely to be less disruptive than highway activities at Waddell Bluffs, no monitoring of the adjacent marine environment is recommended for marine disposal at any continuous cliff slides. If there is some doubt about this recommendation for a particular site, it should be visited in a field trip with scientists who work on these processes and Caltrans staff including environmental managers and local maintenance crew to assess potential special monitoring requirements.

3.3 Disposal on creeping landslides

There are a number of slow creeping landslides along the Big Sur coast which can be used to dispose of landslide debris from the highway (Figures 9-11).

Ecological Evaluation
There are no detectable ecological impacts to the marine environment from debris disposal on creeping landslides. They are too far from the ocean for direct sediment inputs.

Monitoring
No marine monitoring is recommended for creeping landslides receiving highway landslide debris. If sediment input to the local marine environment becomes likely at a site, it should be visited in a field trip with scientists who work on these processes and Caltrans staff including environmental managers and local maintenance crew to assess potential special monitoring requirements.

3.4 Disposal after episodic small slides, rock falls, and other highway activities

There are a number of episodic small landslides and rock falls onto the highway (Figure 1). Many of these landslide features are on both sides of the road, and the natural sink for the debris is the lower slope and the adjacent beach and marine environment. Like the continuous cliff slides, the down slope slide face is the best location (Figure 12) for disposing of landslide debris deposited on the highway from the upper part of the slide. In some cases, the slide toe is not adjacent to the marine environment and the debris is not disposed of on the west side of the highway because the slide does not continue here or the area is vegetated with native plant communities or should be. This debris can be placed on creeping slides. There are also a number of eroding sea cliffs that can use large rocks deposited on the highway to help armor the cliff and therefore the highway above from wave erosion (Figure 12). Highway construction and maintenance activities such as bridge replacements, drainage structures, and crib walls are similar to episodic small slides.

Ecological Evaluation
There are no detectable ecological impacts to the marine environment from debris disposal from small episodic landslides or from rock falls. These debris falls involve small volumes of sediment compared to the catastrophic landslides or the continuous cliff slides.

Monitoring
No marine monitoring is recommended. If ecologically significant sediment input to the local marine environment becomes likely at a site, it should be visited in a field trip with scientists who work on these processes and Caltrans staff including environmental managers and local maintenance crew to assess potential special monitoring requirements.

4. Conclusions, Summary and Recommendations

With the exception of catastrophic landslides, no other significant ecological impacts are known from landslide debris disposal into or near the marine environment along the central and northern coastal sections of Highway One. These sediment inputs and movements through the local marine habitats are natural processes. However, the catastrophic landslides involve such large inputs of sediment that there are significant ecological impacts.

Establishing native vegetation on bare ground is the most important positive action to reduce potential landslide erosion onto the highway and into the marine environment. This is true for all types of disposal operations, including the catastrophic landslides. The erodable buttress or fill of the manipulated catastrophic landslide (Figures 2-5) should be stabilized with native vegetation as soon as the fill is deposited. This is essential mitigation for debris disposal in the fill, and will reduce ecological impacts to the adjacent marine environment. Protocols for planting steep landslide faces are being developed at the McWay site, but the extremely positive role of vegetation in stabilizing erodable soil is well established from many other less steep landscapes including stream banks, river dikes, farm buffers, many roadways, and grading sites at development projects.

The vegetation of bare soil along the highway and on disposal features such as the fill of a catastrophic landslide is the most important recommendation for mitigating and reducing potential impacts to the marine environment.

The second major recommendation is to follow the monitoring protocols outlined for the disposal of slide debris after catastrophic landslides such as those at McWay Rocks and Lone Tree Creek (Figures 2-5). No monitoring is recommended for any other type of marine disposal because they involve small volumes of sediment compared with the natural movement of sediment in the local marine environments.

5. Appendix: Marine Disposal Impacts at three Long-Term Research Sites

The general research strategy at Waddell Bluffs, McWay Rocks and Lone Tree Creek was to explore ecological changes caused by sediment disposal from construction and maintenance of sections of Highway One which are disrupted by landslides; and to compare these anthropogenic disposal disturbances to natural processes of sediment burial, sand scour, and fine sediment suspension and deposition. This appendix provides a background description of research results after 5 years of monitoring the sedimentary habitats and marine communities at Waddell Bluffs (Bretz 1995, Moss Landing Marine Laboratories 1996), 6 years at Lone Tree Creek (Moss Landing Marine Laboratories 1996), and 10 years at McWay Rocks (Burdett 1992, Kiest 1993, and Kim et al. 1998). These three sites are the most intensively and extensively investigated marine disposal locations for Caltrans operations along the central and north coast.

5.1 Waddell Bluffs

5.1.1 Physical Setting

Waddell Bluffs is one of the largest and most active continuous cliff landslides along the coast. Regular maintenance is required to prevent slide sediment from obstructing the highway, to move material across the road, and to dump stockpiled sediment into the adjacent marine environment. State Highway One cuts across the slide face just south of Ano Nuevo Island. The bluffs are highly unstable Franciscan shale. Landslides are common and road maintenance is a constant problem.

Before the road was constructed, sediment moved down the slide face and was deposited on the upper beach where it was eventually eroded by wave action. Episodic slumping of slide material was highest during periods of heavy winter rains. The highway interferes with the natural pattern of movement. Sediment is captured in a ditch along the east side of the road and periodically moved to the west side where it is stockpiled at the upper edge of the slide slope. Stockpiled sediment is pushed over the edge and down the slope during winter months when natural beach erosion from winter storm waves is highest. Therefore, the slide is continually dumping material which Caltrans moves and dumps into the intertidal zone, the natural sink.

5.1.2 Biological Patterns

The marine habitats below the slide area are sandy beaches and rocky shale benches. Sand moves naturally on and off large sections of the rocky habitat each year. Winter storms expose the benches, and sand moves over them in late spring until fall. This is one of the best physical habitats to explore the ecological impacts of sand burial because large areas of the flat, broad benches are covered by sand to different depths and for different periods of time. It is thus easy to locate regions which are disturbed more or less severely and frequently by sand burial. Most rocky intertidal habitats have more complex vertical and horizontal changes in topography where patterns of sand burial are equally complex in both time and space. The shale benches at Waddell Bluffs are ideal for investigating the relationship between sand burial and biological communities.

Sand burial plays a major role in structuring rocky intertidal communities under Waddell Bluffs. This is a natural process. The gradient of sand burial produces four distinct intertidal communities. The presence of each community is correlated with the depth and cover of sand over the underlying shale. The sites covered with the deepest layer of sand (as much as a meter) for the longest number of months harbor only a few weedy or opportunistic macroalgae, especially *Ulva* sp. and *Porphyra* sp. The rock is uncovered for only several months each year, when opportunistic plants colonize the new space from spores floating in the water or perhaps left dormant under the sand. Marine invertebrates such as limpets, chitons, and snails that live at similar intertidal elevations without sand are not present. They cannot tolerate long periods of sand burial.

A mixture of fleshy red and brown algae bloom on rocks covered with a similar thick layer of sand. These sites are apparently open for colonization slightly longer or are wetter than the *Ulva* and *Porphyra*. region. The most abundant species is *Mastocarpus papillata,* which apparently colonizes the sites from spores or vegetative cells remaining on the rock. The mixed algal species do not broadcast spores through the water as readily as the more opportunistic *Ulva* and *Porphyra*.. Marine herbivores, primarily the molluscs, are still absent in the mixed algal sites.

The thick layers of sand covering the *Ulva* and mixed algal sites harbor the same beach fauna as natural beaches without underlying shale. The most abundant species are beach hoppers (*Orchestoidia*) along the high intertidal beach and mole crabs (*Emerita*) along the mid and lower beach. Large numbers of mole crabs settle on the beaches in late winter and spring from pelagic larvae. Hoppers colonize the new beach from adult amphipods carrying young in ventral brood pouches.

The third major community is formed by the filamentous red algae, *Polysiphonia pacifica.* Here the sand is present in a thin layer, rarely more than 5-10 cm thick. But the thin deposit is present throughout most of the year, although it is thinnest during periods of heavy storm waves. *Polysiphonia* grows through the sand and stabilizes it. As a result, the sand harbors many infaunal invertebrates that are not found on the highly shifting sands of the normal beach. For example, tube-dwelling spionid polychaete worms are common. They cannot build tubes and live on the extremely mobile sandy beaches. The dominant animals here are highly active burrowers such as beach hoppers and mole crabs.

The site with the least cover of sand is dominated by colonies of sea anemones- one of the most sand tolerant animals on rocky shores. Anemone patches commonly harbor another sand tolerant algae, *Neorhodomela larix,* and sometimes *Ulva* slightly higher on the shore. Anemones can extend their bodies through a layer of sand over 10 cm thick (Pineda and Escofet 1989), but there are rarely more than several centimeters of sand in the anemone sites. Again, these thin layers are often present throughout the year, although they are thinnest during periods of strongest wave action.

These four intertidal communities were observed on shale benches under the Waddell slide and on shale benches at Scotts Beach, where there is a similar natural seasonal movement of sand on and off the rock but no sediment dumping for highway maintenance. However, the shale benches are more extensive at Waddell Bluffs and harbor a much larger area of biological communities impacted by sand burial.

5.1.3 Highway Activities

Road maintenance moves approximately 15,000 cubic meters of slide sediment across the highway each year. Much of this material would eventually fall to the beach if the highway did not interfere with the natural flow of sediment movement. By comparison, approximately 50,000 cubic meters of sand moves on and off the natural pocket beach at Waddell Creek by seasonal changes in wave action. This beach is about 800 meters long, bounded on both ends by rock benches. The northern end is the beginning of Waddell Bluffs. About 12,000 cubic meters of sand is deposited on the shale benches under the bluffs each year. Most of this material is removed each winter by storm waves. Sediment dumped from the Waddell slide is a fair fraction of the sand which is naturally moved on and off local beaches, both with and without underlying shale benches.

There is no evidence that the dumped sand impacts the exposed rock benches either physically or biologically. Dumping of slide material is done during the winter, the period of greatest beach erosion and exposure of shale benches. Estimated daily removal of slide material by wave action is about 36 cubic meters/day during strong winter storms and 5 cubic meters/day during the calmer summer season. The rocky surfaces remain exposed despite sediment dumping for highway maintenance. The composition of sediments that characterize the slide are very different from the medium to fine grained sands of the adjacent intertidal beaches. No traces of silt or clay sediments from the slide deposits were found in any grain analyses of sediments cored near the benches. Presumably, the slide sediments are light enough to be removed and transported away from the area with successive tides. The general seasonal development of biological communities is similar between Waddell Bluffs, an area with landslide material dumping, and Scotts Creek, an area without highway landslide activities. Nature moves a much greater volume of sand on and off the shale reefs each year, and plays the major role in structuring intertidal communities.

The relationship between sand burial and community patterns at Waddell provides the best ecological model for potential impacts of sand burial in other rocky intertidal habitats.

5.2 McWay Rocks
5.2.1 Physical Setting

The landslide above McWay Rocks, along the Big Sur coast, occurred after heavy rains in the winter of 1982-83. The slide closed State Highway One for almost two years. The natural slide deposited some material directly onto the boulder and cobble beach below the slide and would have lead to an increase in erosion from the slide face and into the marine environment. However, most of the slide was on the upper hillside and was not deposited in marine habitats. The slide was stabilized by moving over 3 million cubic meters of soil from the upper face (above the highway) of the slide and placing it at the toe (Figures 2-3), which was designed to erode and eventually stabilize west of the highway. The new slide toe was constructed by pushing sediment from the top of the slide over the seaward edge and thus moving the new toe over 75 meters westward. This buried a large area of intertidal habitat as well as subtidal marine environment. Between 1983 and 1992, over 900,000 cubic meters of sediment eroded from the lower slide face (below the highway) with an additional amount eroding from the upper slide and poorly vegetated edges. Sediment erodes from the slide face with rain and runoff, and from the toe by the action of waves.

Unfortunately, none of the slide sediment has been adequately stabilized with native or any other vegetation, especially the lower face and toe. The drainage system from the upper slide empties directly onto the lower slide and has eroded a deep canyon to the slide toe (Figure 3). In ten years approximately 257,000 cubic meters of sediment eroded from this canyon. In the last two years (1996-97) even more sediments eroded to produce the major topographic feature of the slide (Figure 3). The erosion of the canyon under-cut the highway in the winter of 1997 and was repaired with the construction of a new bridge, where there is an ongoing project to stabilize the fill slope with native vegetation.

Observations on the physical and biological impacts of the slide did not begin until almost three years after the slide was manipulated to reopen the highway. The structure of natural intertidal and subtidal habitats and communities before the slide are unknown. However, a few aerial photographs provide views of the slide face and intertidal areas before sediment was dumped. The physical and biological nature of potentially similar environments without a landslide disturbance provide additional insights into what the disturbed area might have been before the slide was manipulated.

The manipulated slide material covered approximately 23,700 square meters of intertidal boulders, cobble, and gravel beach. The actual size of the beach was not measured prior to the dumping but can be roughly estimated from aerial photographs. The natural beach was completely buried under the slide toe. The adjacent subtidal environment was also buried with slide sediment. The new slide toe continued underwater as a large submarine bench sloping gently from the base of the beach to a water depth of about 7-9 m and then more steeply to the natural bottom at water depths of 20 m or more. The subtidal bench of slide sediment buried rock pinnacles and fine sand bottoms with a coarse and poorly consolidated sand which is much more prone to movement by wave action than the natural, fine sand deposit.

The manipulated landslide created sand beaches on both sides of the slide which were not present before sediment was moved. The beaches are maintained by constant erosion of soil from the slide toe and canyon, and held in place by the subtidal bench, formed of slide material. The natural bottom slope along the coast is gradual to the beach, where it slopes steeply, and does not include the broad subtidal bench produced by eroding slide sediment.

The new slide toe buried intertidal rocky habitat and subtidal rocks and sand bottom, including the original boulder and cobble beach. The bench buried subtidal rocks and the bases of larger pinnacles. The larger pinnacles were probably in water depths of 20-25 m before the landslide. Their inshore edges are now against the bench, around 9-10 m. As a result, pinnacle communities that were many meters from the sea floor are now next to it. Since the slide deposit is a poorly sorted and loosely consolidated coarse sand, it is easily moved by wave-generated bottom currents resulting in intense sand scour next to the pinnacles. Next to the direct burial of habitats, the most conspicuous impacts are caused by sand scour. These impacts are more severe around the slide compared to all but a few natural habitats, where strong wave action bashes sand, gravel, and cobble against vertical rock walls.

Plumes of fine suspended sediment form in the nearshore marine environment as landslides naturally erode, primarily from wave action and rain. The presence and size of plumes depends on several factors but especially the degree of armoring by large boulders and also the cover of native plants. Larger rocks remain at the bases of slides as finer sediments are eroded by wave action and rain. Some slide deposits contain more larger rocks and thus have greater potential for developing a heavy armor from wave action than those without boulders in their sediment matrix. Slides with heavier armor often have smaller plumes spreading into the nearshore marine environment. Similar plumes of suspended sediment occur around coastal creeks and rivers.

The McWay slide has relatively few large boulders in the slide debris and no significant rock armor was developed before the 1982-83 rains and slumping event. A plume of suspended sediment was observed by local residents for at least decades before the 1982-83 event, and is also seen in the earliest aerial photographs. It was probably present much longer since a number of smaller slides contribute to the beaches in the semi-protected cove behind the offshore rocks. The plume from the manipulated landslide is larger and more turbid, but the early observations and aerial photographs are inadequate for making a direct comparison before and after the slide was manipulated.

5.2.2 Biological Patterns

The manipulation of the McWay Landslide caused severe impacts to local marine communities, unlike Waddell Bluffs. Rich bottom communities were buried in the intertidal and subtidal environments. New intertidal and subtidal beaches were formed. Although impacts from the new sediment plume are observed only within 100 meters of the slide, sand scour may be increased more than 1/2 km from the slide. The impacts below and near the slide are obvious.

Natural sand scour produces a distinct zonation of organisms in the subtidal rocky habitats. Where scour in most severe and horizontal surfaces are present, the only common species are newly settled brown and some red algae. They rarely survive into the next year. On more vertical surfaces, barnacles dominate the space. They are all new recruits that do not survive the scour from winter storms. Above this heavy sand scour zone there is a transition zone with patches of barnacles that colonize small scour marks, and survive more than one year. A few other long-lived species live here because they tolerate sand scour. The best indicators are cup corals such as *Balanophyllia*. Above the transition zone, the dense invertebrate communities show little or no signs of sand scour. This zonation was first discovered in natural surge channels where winter swell throws cobbles and boulders against vertical walls. After discovering this ecological model, it was clear that many rocky habitats around the slide were also disturbed by sand scour.

Sand scour was intensified dramatically by the McWay landslide. The most conspicuous impacts are observed directly under the slide where a number of large rock pinnacles were partially buried with slide material. These pinnacles are covered with a rich community of sessile invertebrates, especially on vertical walls and overhangs. More horizontal surfaces are covered with a mixture of invertebrates and marine algae. Slide sand has scoured and radically modified the structure of vertical wall communities around the slide pinnacles. Lower rock walls are scoured almost bare during winter storms and barnacles settle each spring. Few survive the next winter, except those settling in open patches high on the rocks. The cover of barnacles is thus high and the cover of the usual native wall communities (sponges, anemones,, tunicates) is lower under the slide compared to pinnacles that are not influenced by the slide.

The ecological impacts of sand scour from the slide continue after more than a decade since the slide was manipulated and they are still spreading. The relatively natural conditions may not return for decades. Since our observations began in 1985, we observed the spread of slide material, sand scour, and extensive barnacle recruitment into the northern kelp forest at McWay Rocks. We also observed the spread of coarse slide sand to the south as far as the southern kelp forest and underlying rocky reef.

McWay landslide produces a persistent sediment plume. The plume is formed by a suspension of very fine sediment in the water. It was present before the recent slide, but is larger and more turbid now. Plume impacts can only be detected in the adjacent kelp forests at McWay Rocks. Here the cover of understory algae is significantly reduced below the plume compared to kelp forests without plumes. These impacts are not widespread in the kelp forest, because the kelp apparently forms a physical barrier to the spread of the plume. Therefore, the impacts are largely along the forest border. The plume impacts are not so conspicuous and widespread as sand scour. They primarily influence understory algae, and are less important to animals.

5.2.3 Highway Activities

The natural McWay landslide closed Highway One, but had little direct impact on the nearshore marine environment. Most of the slide material was on the upper slopes of the hill with little sediment reaching the beach. Future erosion by rain would have brought more material to the beach and perhaps produced more slumping with greater impacts to marine habitats. However, the difference between the impacts of the natural and the manipulated slide would remain large.

The manipulated slide buried large areas of both intertidal and subtidal habitats; created new sand beaches at the toe replacing cobble beaches; produced a larger and more persistent plume of suspended sediment; and most important introduced a tremendous volume of coarse sand into the local marine environment. Here the sand continues to scour rocky bottoms and modify the structure of animal and plant communities at increasing distances from the slide.

The ecological impacts of the landslide disposal occur naturally in the local and regional marine environments, but on a smaller spatial scale. None of the existing, active landslides along the central and northern coast introduce such large quantities of sediment into the nearshore so rapidly. The most active slides, such as those at Waddell Bluffs, Bolinas Headlands, and Lucia, deposit relatively small volumes of sediment at the upper beach more or less continuously. The manipulation and massive movement of the McWay slide produced an extreme physical and ecological event. Landslides that move this far into the marine environment must be very large and probably occur naturally, but infrequently, perhaps every 100 or 1000 years.

Significant and certainly avoidable erosion of the slide face continues because of poor cover of native plants. However, experimental revegetation of the slide fill began last spring and should lead to significant decreases in erosion if not complete stabilization.

5.3 Lone Tree Creek

5.3.1 Physical Setting

Highway One crosses a long section of steep coastal bluffs between Muir Beach and Stinson Beach just north of San Francisco. The Franciscan shales in the region are especially susceptible to landslides. A large section of the cliffs near Lone Tree Creek failed during the recent Loma Prieta Earthquake in October 1989, ripping away the road and closing Highway One for almost two years between Muir and Stinson Beaches. Lone Tree landslide was active before the recent earthquake, necessitating periodic road repairs and slide manipulations.

The highway was stabilized and reopened in the same general manner as the McWay landslide. The upper slide was excavated and moved to the lower slide which extended the slide toe about 50 meters into the nearshore marine environment. About one million cubic meters of slide material was moved during the construction. The slide toe buried almost 6 acres of rocky intertidal and subtidal habitat as well as some sand bottoms to a water depth of several meters. Many large boulders were placed near the toe of the slide during the construction to impede erosion by waves. The slide face slumped in several locations and is likely to continue eroding by large slumps and surface erosion.

The marine environment in front of the slide is a highly turbid region primarily from erosion of local coastal cliffs having a high fraction of fine material in the Franciscan shales. There are also more regional inputs of suspended sediment from the San Francisco Bay. Underwater visibility is often zero, and is exceptionally good at one meter. Dense sediment plumes are present all along this section of the coast. The densest plumes occur near active landslides such as Lone Tree Creek. This plume was present before the slide was manipulated and was largest and densest during construction, when large volumes of sediment were dumped directly into the ocean to construct the new slide toe.

5.3.2 Biological Communities

The burial of native habitats and communities is the most significant environmental impact of the Lone Tree slide. Rocky boulders were buried in the intertidal and subtidal habitats. They harbored a limited flora and fauna on the intertidal rocks, but a relatively rich and cryptic invertebrate fauna on subtidal rocks. A coarse sand beach was formed along the south side of the slide and a cobble and boulder beach formed under the slide and to the north. Many larger rocks still protrude above the sand beach, but are heavily scoured by beach sand that was not present before the slide. The larger rock boulders under the slide are being colonized by relatively opportunistic species of intertidal algae and animals. However, these rocks are still moving and shifting as the slide face erodes and will thus change as potential habitat for marine organisms. They should be periodically monitored to document the recovery of intertidal communities.

Sand scour is more conspicuous and severe along this area of coast than in any other section of California we have observed. The lower portions of the pinnacles and rocks are often covered with recently settled barnacles. These settle after the period of heaviest winter scour, and rarely survive through the next winter scouring. Some of the low rocks (< 1 m tall) are completely covered with barnacles. Scour also opens spaces within the denser invertebrate communities, which develop higher above the sediment. These spaces are often colonized by barnacles, and many survive beyond the first year becoming larger. The result is a mosaic of barnacle patches among the other sessile invertebrates, often the red anemones- a mosaic of red and brownish-white patches. Above this zone of intermediate disturbance, invertebrates that are less tolerant of sand scour flourish. A number of low-growing sponges and bryozoans are also tolerant of sand scour and persist on lower rocks through periods of winter scour.

No new sand scour was detected at a series of rocky pinnacle habitats closest to the slide fill. No impacts of the plume of suspended sediment were detected at Lone Tree. Local algal communities are already poorly developed, because of the low penetration of light through the naturally turbid nearshore waters. The biological impacts of the Lone Tree do not extend beyond the toe area and are much less severe than they are at McWay Rocks, but involve the same basic processes of burial, scour, and sediment suspension.

5.3.3 Highway Activities

The unmanipulated natural landslide at Lone Tree has been active and several times in the past caused road closures and significance highway maintenance. A fairly unstable slide toe was present before the earthquake as well as a distinct plume of suspended sediment. However, there was no significant burial of marine habitats from the natural slide and no large inputs into the subtidal environment.

The manipulated slide (Figures 4-5) buried large areas of intertidal and subtidal marine habitats and introduced a large quaintly of new sand into the marine environment. The plume of suspended sediment also increased in size and density after slide manipulation, but decreased in size and density since construction activities ceased in the summer of 1991. The plume size and sediment inputs from the slide increase with erosion from winter rains and storm waves. Like the McWay slide, Lone Tree may be a model for an extreme landslide event, one occurring every 100 to 1000 years. None of the natural slides extend so far into the ocean and involve such a large volume of sediment eroding rapidly into nearshore habitats. On the other hand, the Lone

Tree environment and marine communities appear to be much more resilient to sediment disturbance than they are at McWay Rocks.

The manipulated slide was designed to stabilize the road while disposing of extra slide material on the lower face and toe. The slide is designed to have the lower material erode into the ocean until an equilibrium is reached. Unfortunately, there was only limited revegetation of the top of the slide fill and most of the lower slide face is bare ground. The equilibrium will certainly develop much faster with the soil stabilizing roots and leaves of native plants. There is much more colonization of the Lone Tree slide fill by volunteer native plants compared to the extremely sparse plant growth on the McWay slide.

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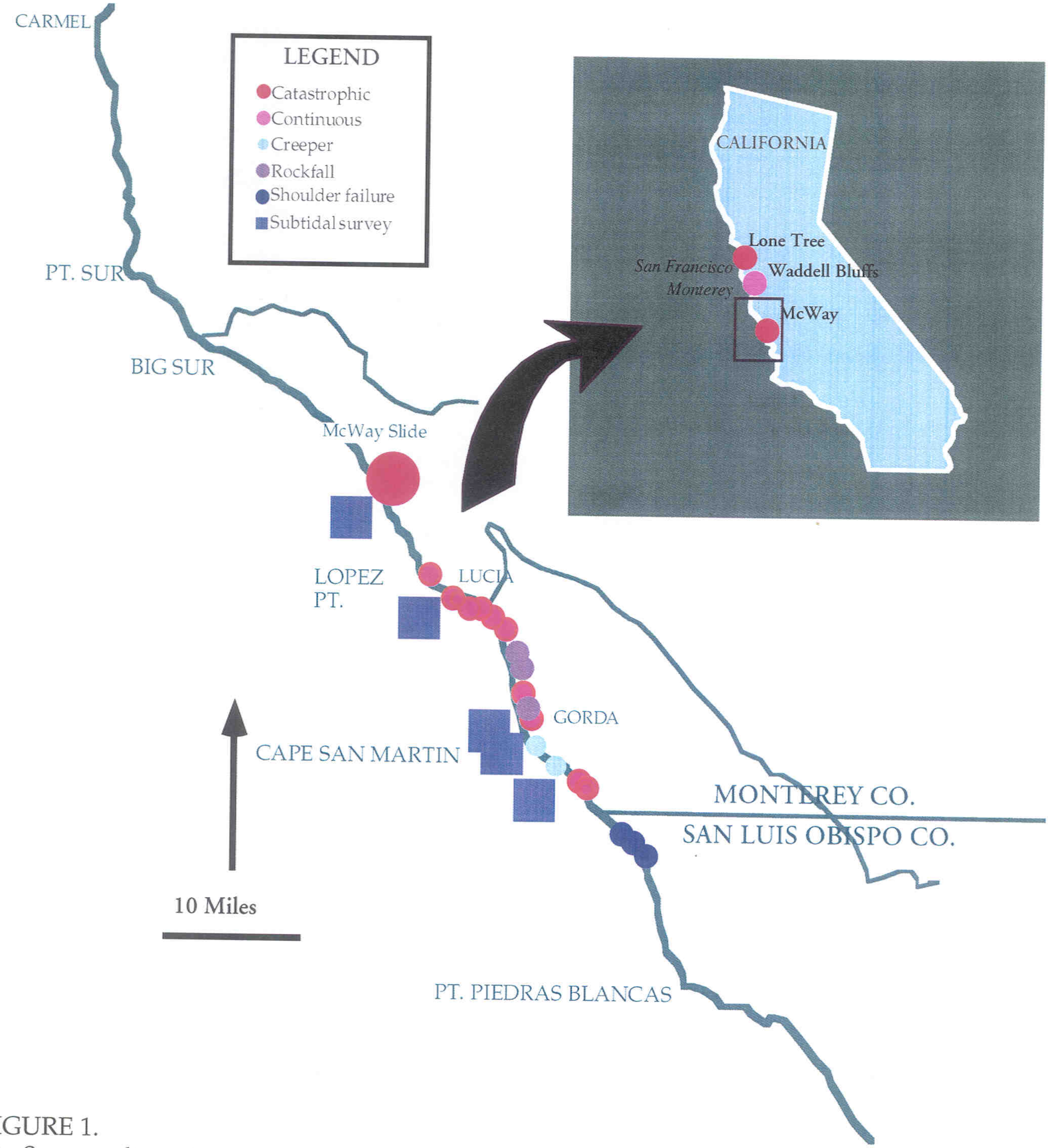

FIGURE 1.
Big Sur coastline of California showing landlside hazard survey locations: catastrophic, and creeper slides, and rockfalls, shoulder failures and subtidal biological survey sites. Insert shows the locations of three major landslides (catastrophic and continuous) of central and northern California.

Figure 2.
McWay landslide manipulation on Highway One along the Big Sur coast in 1997. This catastrophic landslide that occurred in the winter of 1982-83 closed the highway for a year.

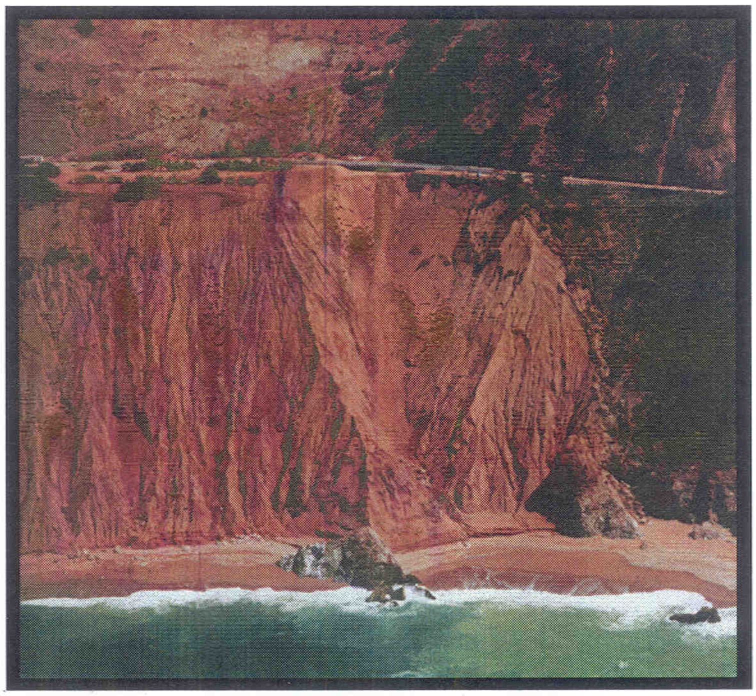

Figure 3.
Close view of the gully eroded in the McWay landslide fill by drainage water incorrectly piped from the upper slide.

Figure 4.
Lonetree landslide manipulation on Highway One north of Stinson Beach in October, 1991. This catastrophic landslide closed the highway for a year.

Figure 5.
Lonetree landslide fill in 1994 showing rock armoring at the toe, large slumps, and surface erosion of the slide face.

Figure 6.
A potential catastrophic landslide area at Big Creek Reserve with a closer view of rock armoring.

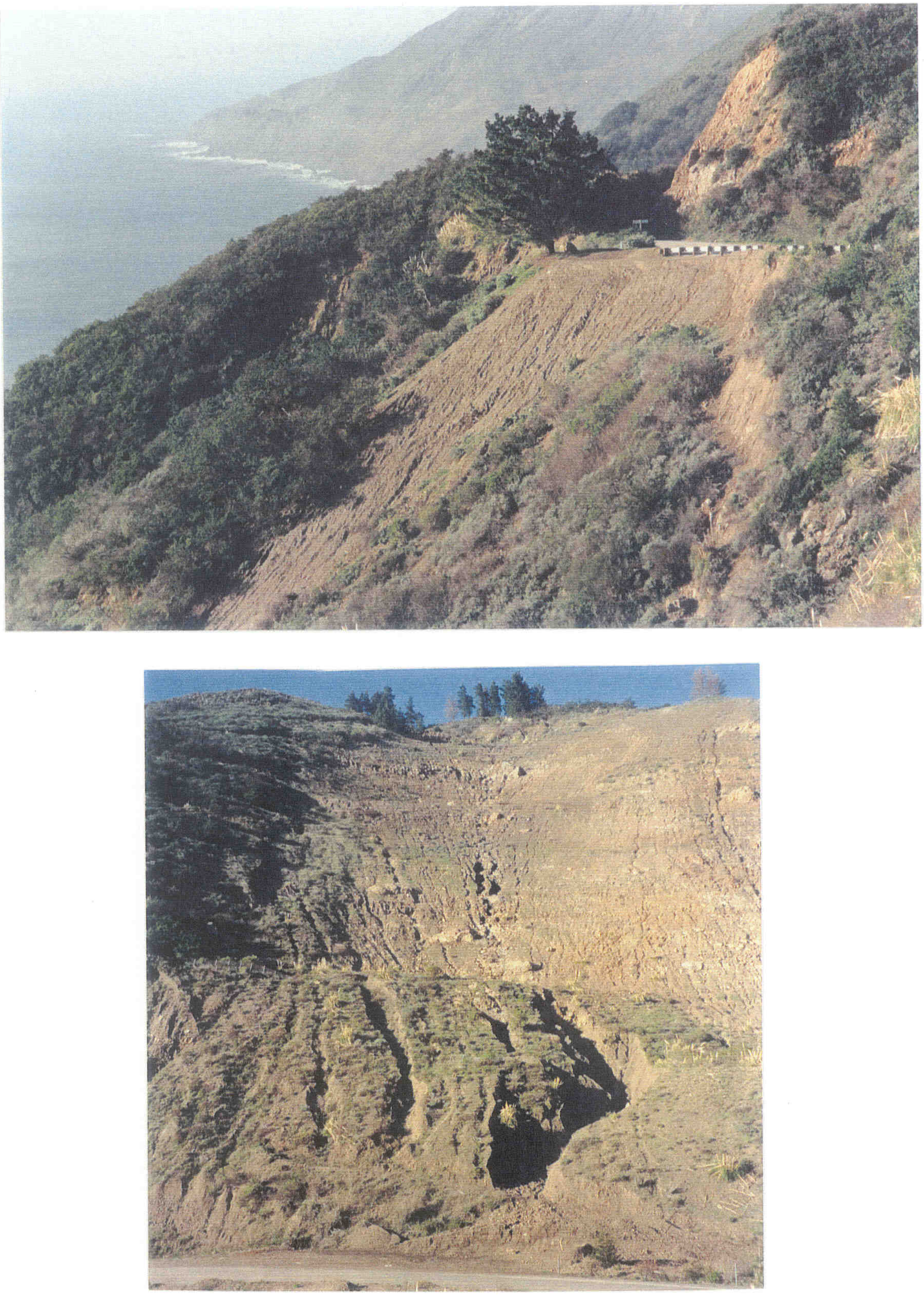

Figure 7.
Eroding roadside landscapes that can be stabilized by native vegetation.

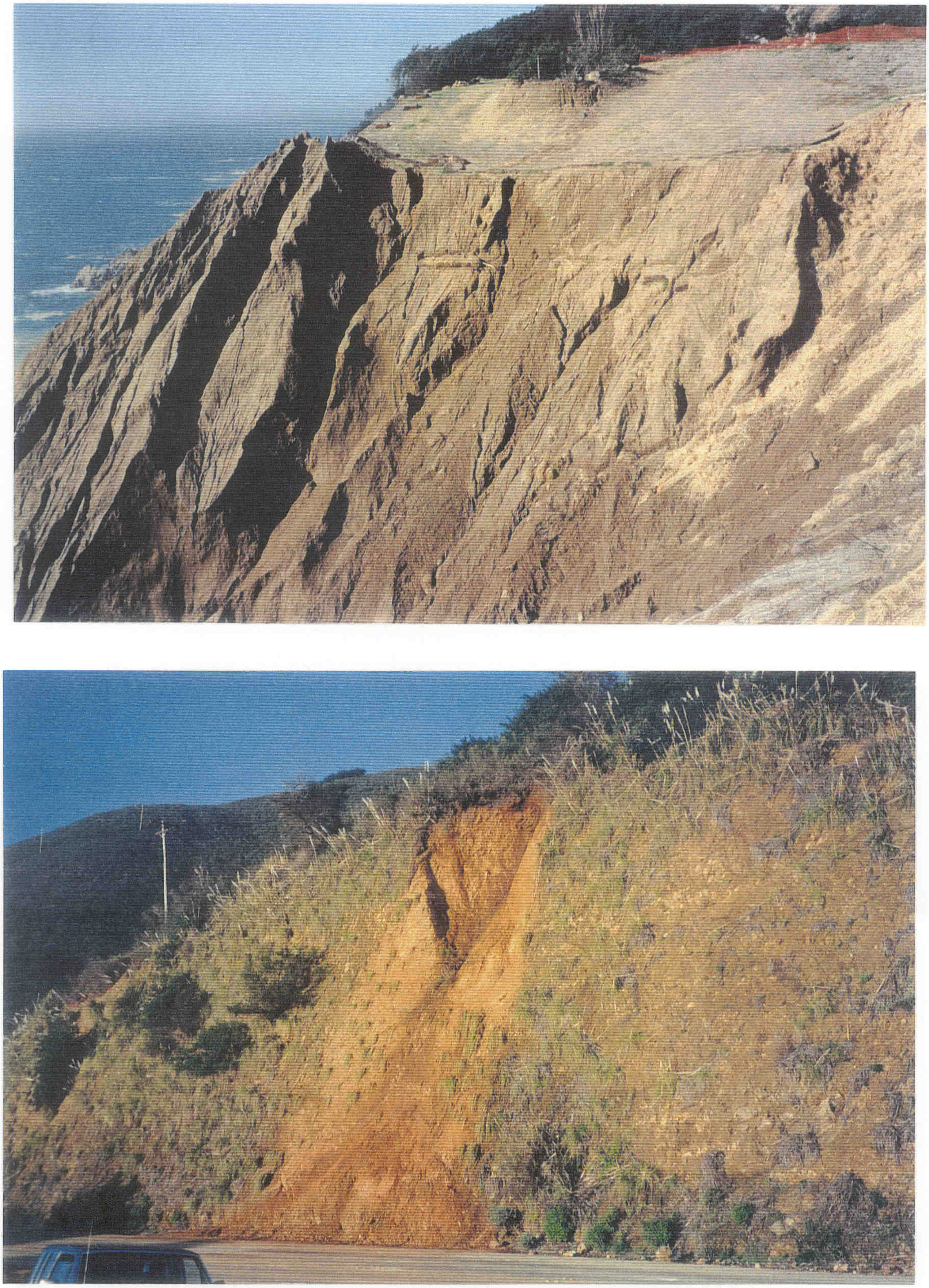

Figure 8.
More eroding roadside landscapes that can be stabilized by native vegetation.

Figure 9.
A creeping landslide along the Big Sur coast and a deposition site for landslide debris on the highway.

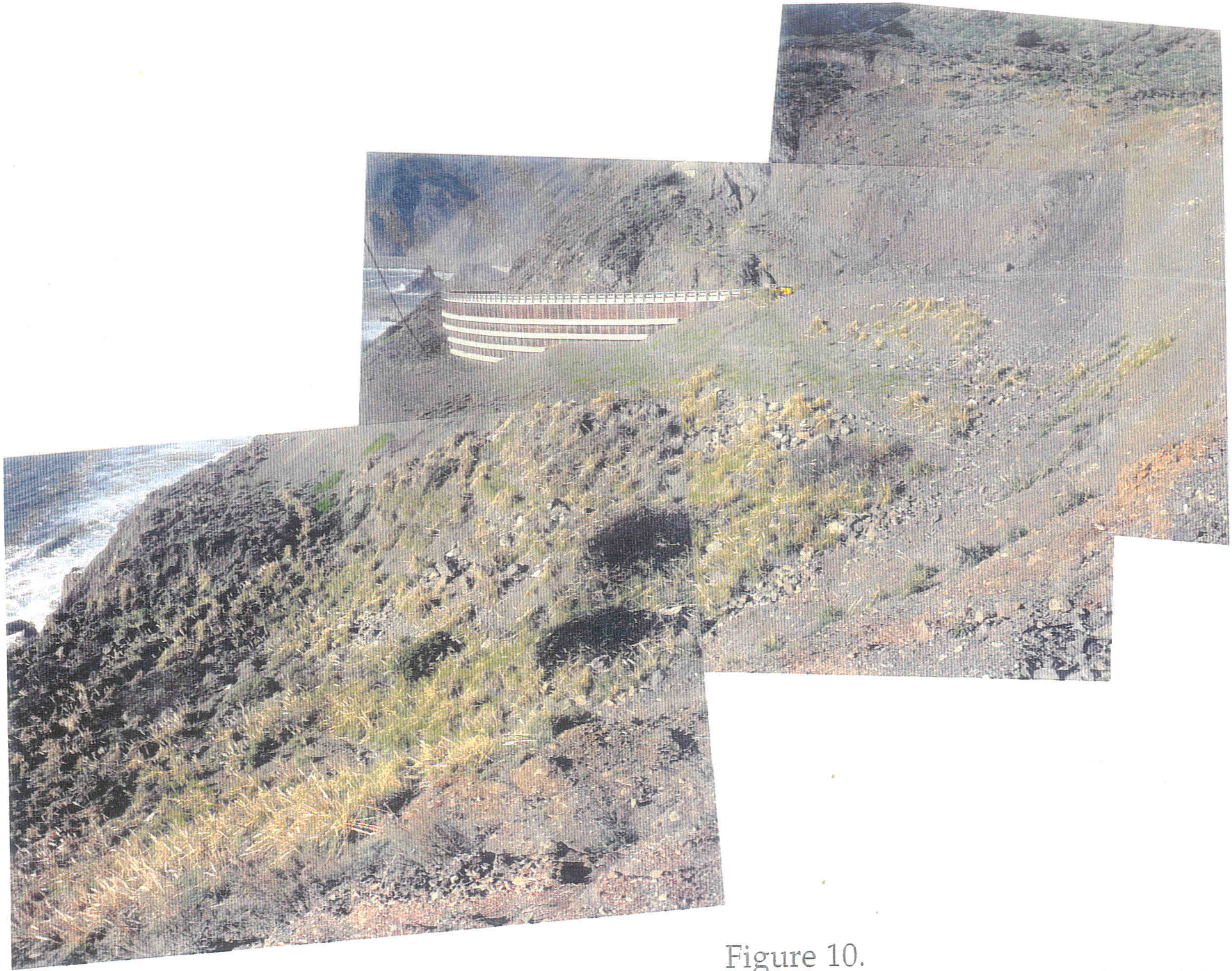

Figure 10.
Another creeping landslide along the Big Sur coast and a deposition site for landslide debris on the highway.

Figure 11.
Two more creeping landslide along the Big Sur coast which are deposition sites for landslide debris on the highway.

Figure 12.
Large rocks falling on the highway are deposited on rocky benches like these.