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# *Paleo-landslides in the Tyee Formation and highway construction, central Oregon Coast Range*

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## ABSTRACT

**Investigation and design-build construction of the Highway 20 realignment through the Oregon Coast Range provides new insight into paleo-landslides of the Tyee Formation and their slope stability. They are widespread, often extending outside of current drainage basins, and much of their morphology has been almost completely hidden by surficial processes. Radiocarbon tests indicate that some of the slide features are older than the testing limits, while other results range from approximately 18,000 to 40,000 yr B.P. The depth of erosion suggests that the paleo-slides may be as old as Pliocene.**

**Geotechnical models of the paleo-slides, needed to analyze potential construction impacts, are developed from subsurface explorations, construction outcrops, radiocarbon testing, monitoring of geotechnical instruments, and geomorphology revealed by light detection and ranging (LIDAR). The process of predicting landslide boundaries (head scarps, toes, lateral and basal shear zones, etc.) for stability analysis of specific landslides has revealed details of their geologic evolution. This field trip provides background on (*a*) the investigations that have exposed numerous giant paleo-landslides, (*b*) findings and interpretations of the age of the landslides and (*c*) methods that are being employed to mitigate landslide reactivation.**

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## OVERVIEW

The objectives of this field trip are to observe interpretations of the paleo-landslides and the construction practices employed to mitigate for landslide movement. New road cuts from construction have exposed internal stratigraphy of paleo-landslides; however, the majority if not all of the cuts will be covered due to grading and application of hydroseed for erosion prevention. Also due to the construction activities, the field trip stops may change by the time of the field trip.

In the late 1980s and early 1990s, the Oregon Department of Transportation (ODOT) performed preliminary reconnaissance work and identified three large landslides along or adjacent to the highway realignment that ranged in size from 5 to 21 hectares (13 to 52 acres; ODOT, 1991). In 2003, during the early procurement phase of the construction project, numerous small slumps and earthflows and three, deep-seated landslides were identified along the proposed highway alignment (Foundation Engineering, 2003). In early 2005, a reconnaissance geology map prepared as part of a competitive bid package further mapped the three previous slides, and also mapped about 15 small local slumps and debris flows and a fourth large, deep-seated slide area (Kiewit Pacific Co., 2005, prepared by Shannon & Wilson, Inc.). The deep-seated slides mapped in Shannon & Wilson's reconnaissance were 4 to 18.2 hectares (10 to 45 acres) in size. In 2005, J.J. Roering, J.W. Kirchner, and W.E. Dietrich authored a ground-breaking analysis of deep-seated landslides in the Tyee Formation (Roering et al., 2005) that predicted deep-seated landslides over a majority of the proposed highway realignment using an automated algorithm analysis of the available 10 m digital elevation model. In 2005 and 2006, the selected design-build contractor, Yaquina River Contractors Joint Venture, produced light detection and ranging (LIDAR) imagery of landforms and topography within a 610 m (2000 ft) wide swath along the proposed realignment route. Using this LIDAR data, Yaquina River Constructors Joint Venture mapped upwards of a hundred landslide landforms within the project right-of-way, along with the subdued hummocky terrain and landforms associated with the paleo-landslides, one of which covered upwards of 200 hectares (500 acres)(URS Corporation, 2006).

During the first year of the design-build construction, it became apparent that additional information was needed to understand the landslides and their potential impact on the project and in 2007 specific landslide investigations were initiated to supplement the existing geotechnical database. Predictions of potential landslide boundaries were necessary to develop numerical models for stability and engineering analysis. Landslide interpretation was based on U.S. Geological Survey 7.5 minute quadrangle topography maps; LIDAR data and imagery; field mapping; subsurface exploration with test pits and drill holes; monitoring of subsurface geotechnical instruments; radiocarbon dating; and assessment of soil and rock characteristics, hydrogeologic systems, environmental conditions, and geomorphic features. To date, in all the phases of investigation, 220 geotechnical drill holes have been completed on the project. Instruments have been installed in a number of the drill holes including 66 standpipe piezometers, 49 vibrating wire-piezometers, and 49 inclinometer casings. Test pits (118) have also been excavated along the project.

The site location is shown on Figure 1. Figures 2 and 3 provide select portions of the mapped regional landsides and local landslide features, respectively. A schematic interpretation of paleo-landslide history is shown on Figure 4. Figure 5 shows a generalized shear key construction sequence and Figures 6 through 11 are select photographs of the geologic and landslide materials. Figure 10 shows landslide monitoring results during construction of a shear key in the Cougar Creek landslide

### Geologic and Landslide Materials

Five basic engineering geologic units occur at the project and include: fill, alluvium, an upper layer of slide debris/colluvium, an underlying layer of weathered rock slide debris, and bedrock of the Tyee Formation. Brief discussion of the units, excluding fill, are provided below.

#### *Alluvium*

Thin veneers of alluvium are common within and adjacent to stream or creek channels. On the north bank of Eddy Creek near its confluence with Tributary D, alluvium is buried by landslide debris.

#### *Slide Debris/Colluvium (SDC)*

An upper slide debris unit (SDC) is essentially colluvium with an underlying shear zone. Typical thickness of this SDC is 6–15.2 m (20–50 ft), and rarely up to 24.4 m (80 ft). The SDC is generally thoroughly disrupted and weathered bedrock, occasionally containing lenses of sandstone boulders that are remnants of the sandstone beds. At the base of the unit is a shear zone, which is typically about 6–100 mm (0.5–4 in) thick, and ranges from soft clayey, fine sandy silt to soft silty clay. The SDC is often nested in, or perched on, deeper-seated landslides.

#### *Weathered Rock Slide Debris (WRSD)*

Underlying SDC is a lower unit of slide debris that consists of rock that is dilated and moderately weathered (WRSD) and more coherent then the overlying colluvium. The previously in-place bedrock has progressively disintegrated and weathered through movement of the landslides. Original bedrock conditions are often partially retained in translational block slides, but rotational slump and earthflow slides more quickly destroy its original condition. In addition, the position and depth within the slide mass can result in different degrees of disintegration and weathering.

Thickness of WRSD ranges from 3 to 46 m (10 to 150 ft). Sub-units include "bedded" and "intermixed." Turbidite sequences are recognizable in the bedded unit, which often contains nested shears at the bottom of sandstone beds that range from slickensided bedding contacts to 25–50 mm (1–2 in) thick layers of clayey silt gouge. The turbidite sequences are unrecognizable in the intermixed unit, which has shale/siltstone that is highly sheared or diced and the sandstone beds have disintegrated into sand- to boulder-sized, fractured rock fragments.

### *Basal Shear Zones*

Basal shear zones range from 6 to 13 mm (0.25–0.5 inch) layers of clayey silt gouge, to 0.30–0.46 m (1.0–1.5 ft) thick layers of diced siltstone or sand- to gravel-sized fragments of siltstone in a matrix of clayey silt. The thicker zones could also be described as extremely soft rock or very stiff to hard cohesive soil. The siltstone fragments are often slickensided or polished.

### *Tyee Formation Bedrock*

The Tyee Formation is a fairly uniform sequence of turbidite beds that are jointed and fractured. Typical bedding thickness ranges from 1 to 3 m (3 to 10 ft). In the vicinity of the project, the unit is gently tilted to the northwest and faulted. Primary structures include bedding parallel separations, joints perpendicular to bedding, and fractures associated with uplift and faulting, and landslide movement. Measurements from down-hole imagery and surface exposures show structures of:

- Average bedding 15/325 (dip degree/dip direction azimuth)
- Prominent joint/fracture sets 72/099, 79/185, and 69/354

## Groundwater

Aquifers are typically unconfined within the colluvium and weathered rock slide debris, and perched on undisturbed bedrock. Locally, perched aquifers also occur above low-permeable zones within the landslide debris. Groundwater levels are typically relatively deep within the landslide mass, usually within the lower half. Groundwater varies seasonally and from storm to storm. Continuous monitoring from September 2007 through November 2008 at three priority (construction-related) landslide areas revealed the following.

- Average seasonal rise: 1.10 m (3.6 ft)
- Average storm spike: 1.04 m (3.4 ft)
- Maximum seasonal rise: 2.77 m (9.1 ft)
- Maximum storm spike: 3.57 m (11.7 ft)
- Maximum combined rise: 5.27 m (17.3 ft)

Groundwater appreciably rises when daily rainfall surpasses one inch. Short duration, intense storms produce relatively rapid rises with about a one day time lag following the initiation of the storm event.

## Age Dating

Radiocarbon dating has been performed on eight subsurface samples collected in landslide debris to provide relative dating of the geomorphic features. The locations of samples are shown on Figures 2 and 3. Three of the samples tested carbon dead, while five samples ranged in age from 17,850 ± 100 to 40,920 ± 570 yr B.P. The testing was performed by

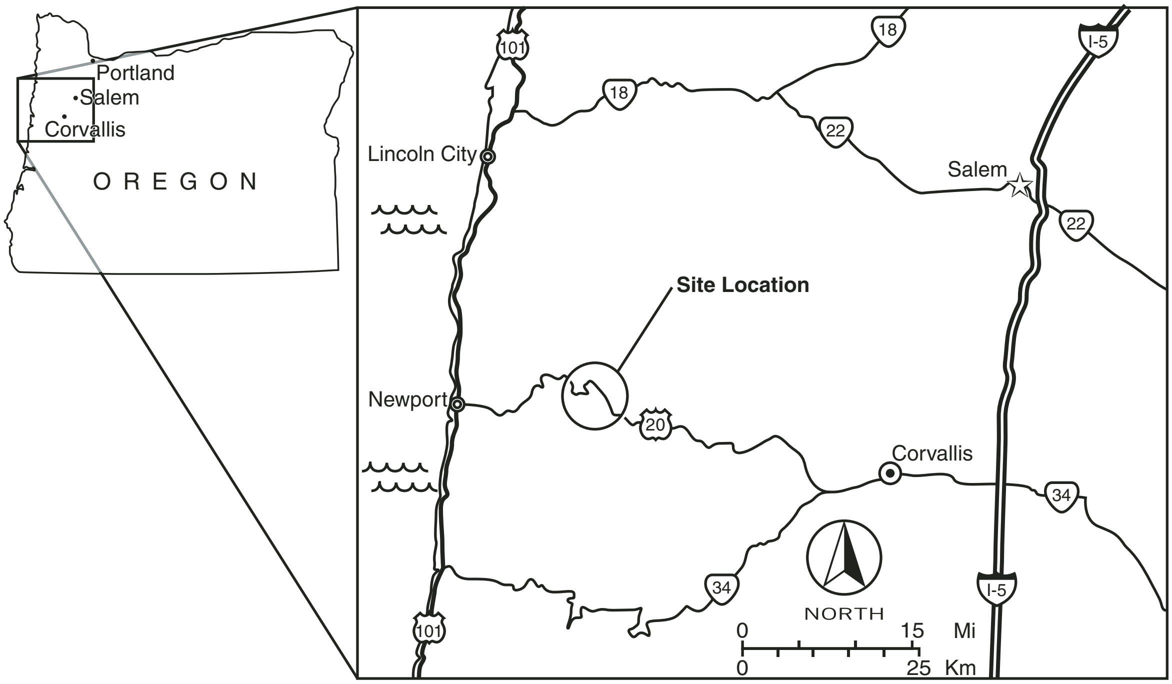


Figure 1. Site location.

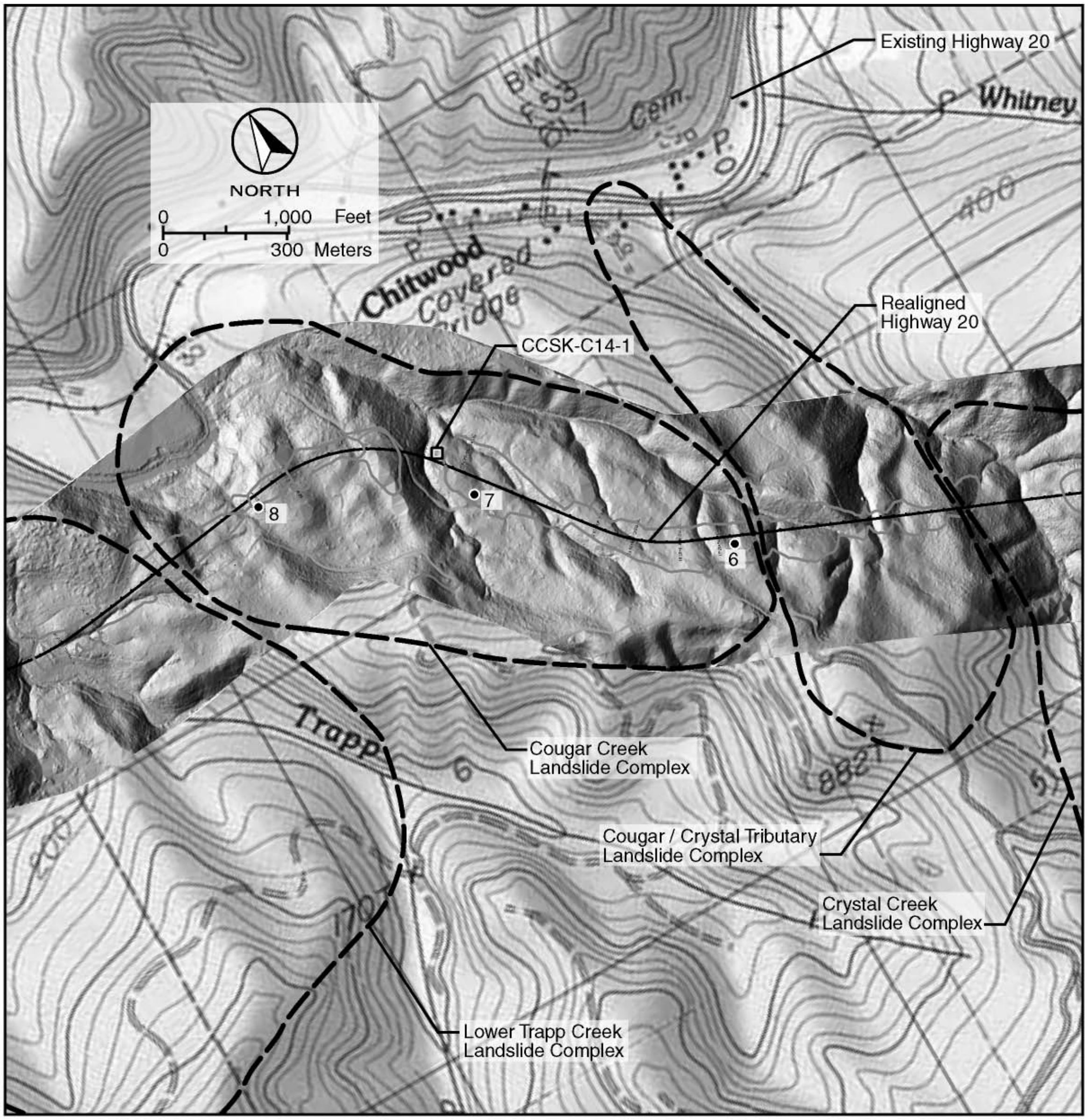


Figure 2 (*on this and following page*). Pliocene-Pleistocene landslide interpretations, with field trip stops and radiocarbon sample locations.

Beta Analytic, Inc., Miami, Florida, using two techniques (radiometric and accelerator mass spectrometry) depending on sample size. One sample was tested per location. Table 1 summarizes the results.

### Interpretation of Paleo-Landslide History

Early geologic reconnaissance work mapped three large bedding plane landslides along the 7 mile route that ranged from approximately 4 to 50+ hectares. As a result of the recent geotechnical investigations and the initial construction efforts, it has become apparent that paleo-landslides cover a majority of the highway alignment, with boundaries that extend beyond the current topographic divides, and with individual slides as large as 200 hectares (500 acres).

The paleo-landslides were likely caused by erosional downcutting through layered stratigraphy and weak interbeds, groundwater and/or precipitation, and seismic activity. Manmade cuts or fills and changes to surface and groundwater conditions may also trigger ground movement.

Marine sediments that would become the Tyee Formation were deposited on a rigid forearc block, which is reported to have been accreted to the western edge of the North American continent during tectonic activity in the upper Eocene and Oligocene.

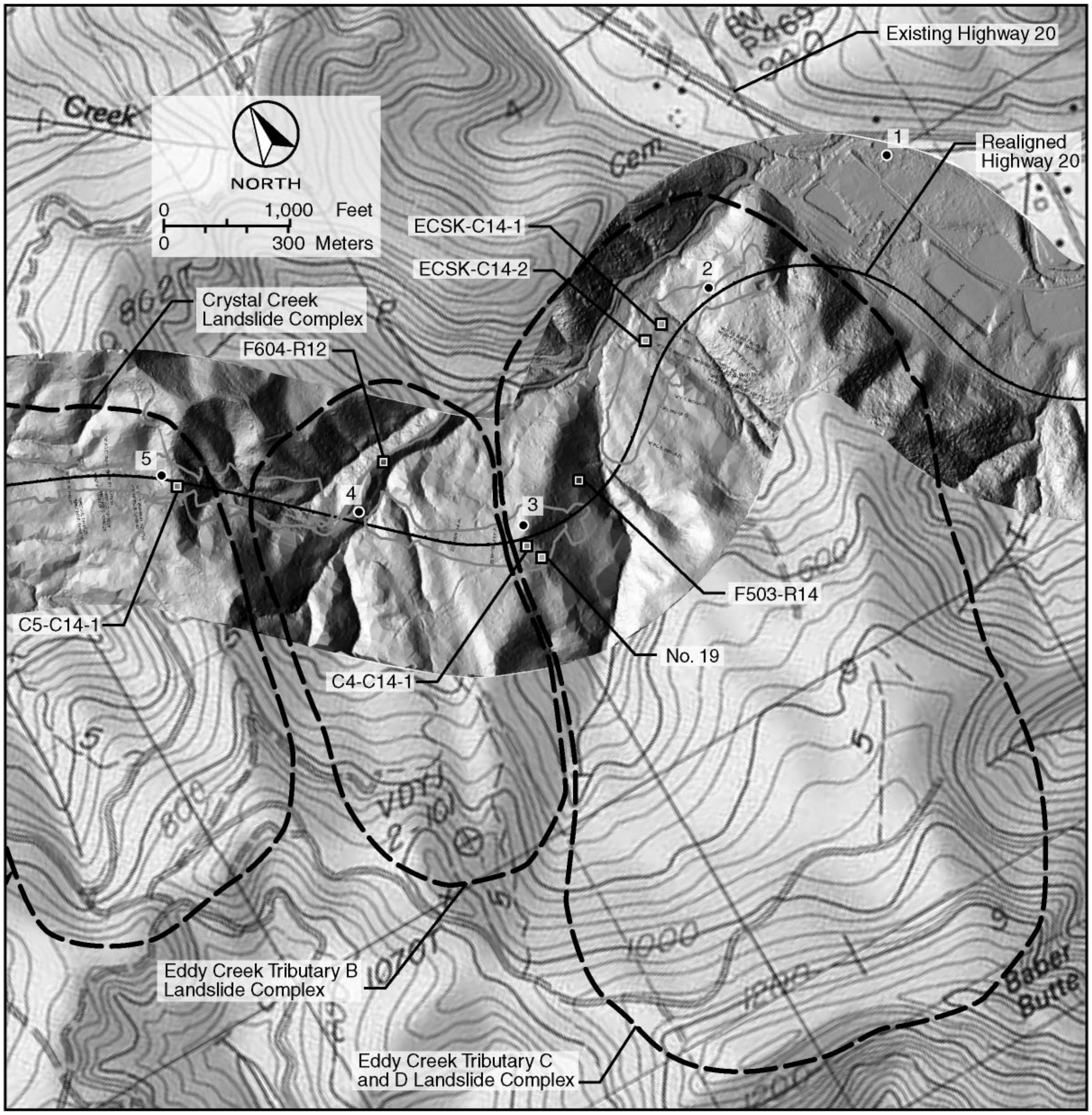


Figure 2 (*continued*).

During accretion the sedimentary rocks were gently tilted and folded, and faulted, including flexure slip along bedding planes (Fig. 4A). Since the accretion of the forearc block, the region has been uplifting at a rate of 0.05–0.2 mm/yr (Kelsey et al., 1996). Landslides probably formed with the onset of erosion (Fig. 4B), and they most likely enlarged as drainages deepened (Fig. 4C). They would be a constant process in relation to uplift, erosion, and base level changes.

Radiocarbon samples collected at Eddy Creek corroborate a period of large, deep-seated landslide activity in the late Pleistocene. Based on climate interpretations for Oregon coast (Worona and Whitlock, 1995; Long et. al., 2007), high groundwater conditions likely existed in Pleistocene and then decreased during early Holocene. With groundwater lowering, the large and widespread Pleistocene landslides probably became less active or inactive during the early Holocene (Fig. 4D). The late Pleistocene landforms have been deeply eroded, and most do not appear to have experienced recent movement; however, some areas have continued activity in the wetter modern climate, which is reported to have initiated approximately 3000 years ago. The youngest landslide features are evident where incised slopes are displaced or shortened locally, or where a slump or earthflow is relatively easy to see.

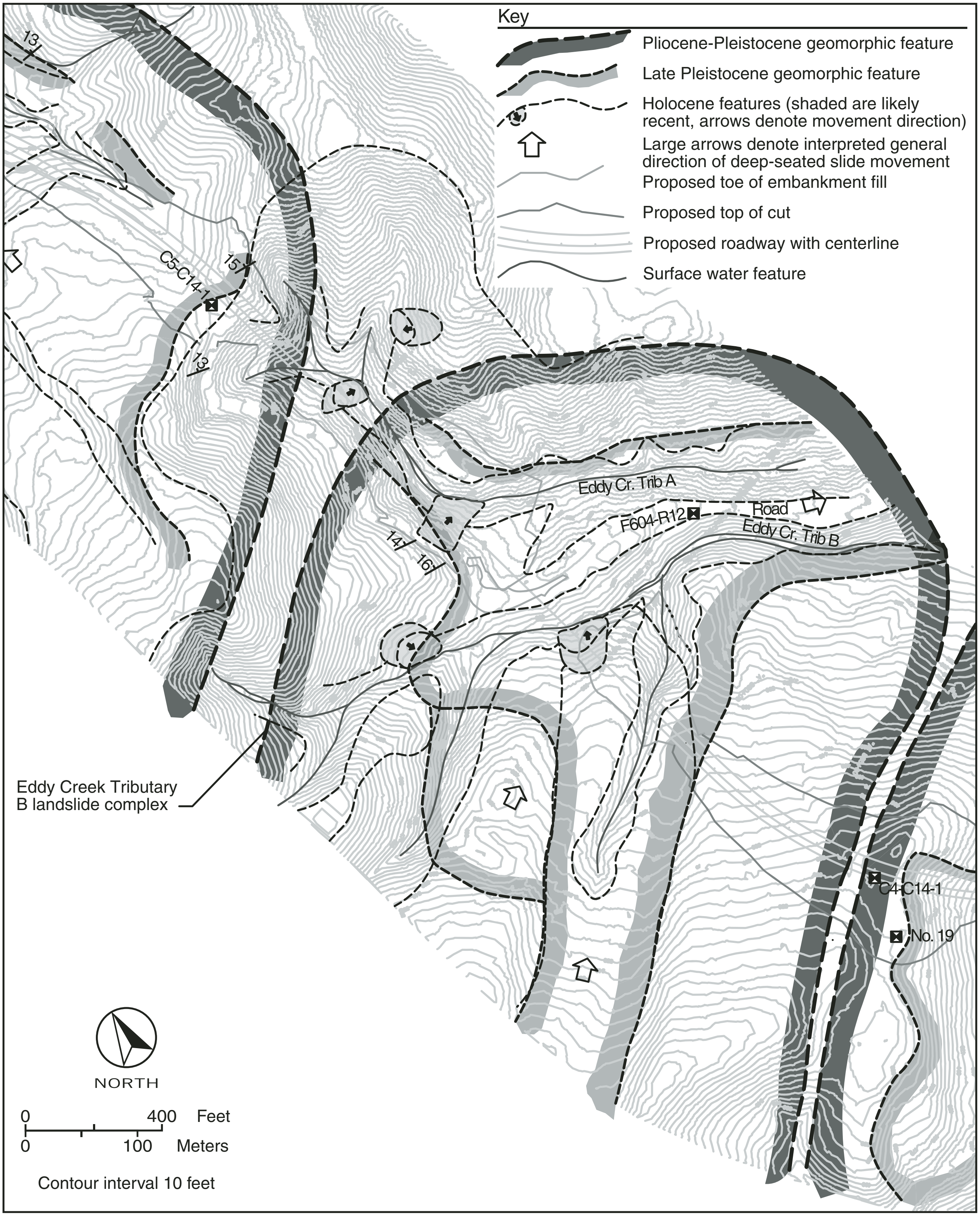


Figure 3 (*on this and following page*). Eddy Creek landslide complexes.

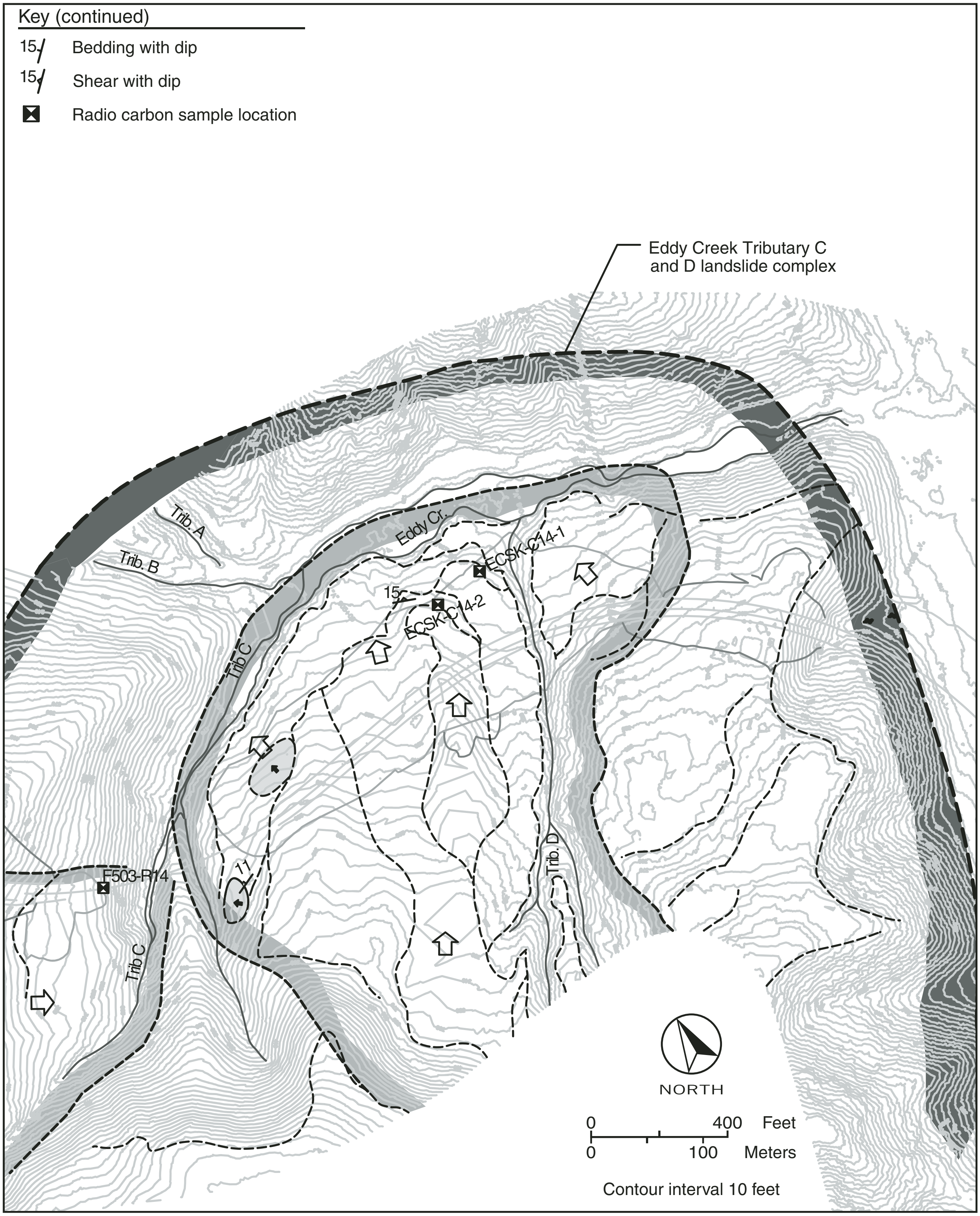
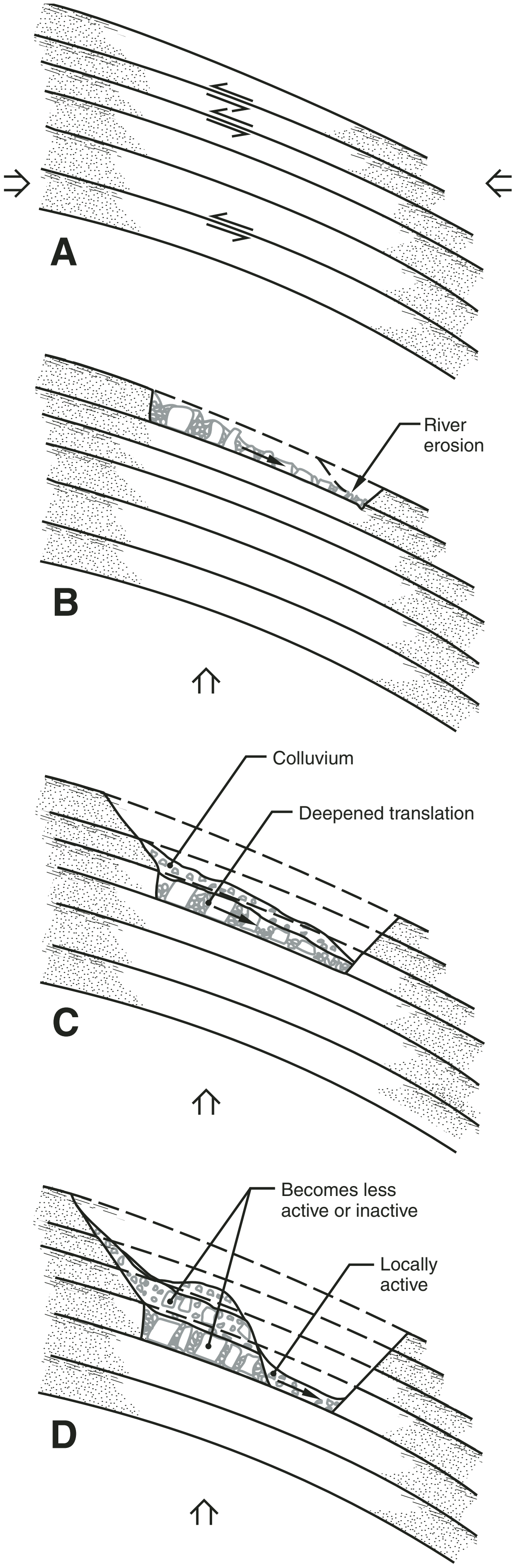


Figure 3 (*continued*).



## Construction and Mitigation Methods

The proposed highway realignment traverses varied topography requiring several aggressive cut slopes, high engineered fills, and eight bridges. Portions of the highway alignment traverse regional-scale, ancient landslide complexes (see Fig. 2), with smaller, nested landslides within the regional complexes. To date, landslide mitigation has been designed for ten locations, including abutments for four of the bridges. The mitigation designs have been necessary in areas where existing landslide terrain is being impacted due to loading by placement of large engineered fills as well as unloading due to excavation of cut slopes. Mitigation techniques include: removal of small-volume, surficial landslide masses; placement of toe buttresses; shear keys constructed at or near the landslide toes; regrading of slopes; drainage; and various combinations of all of the above. Mitigation designs have been applied to landslide masses that have been identified but have not shown significant movement, as well as to active slope failures.

Limitations and challenges to landslide mitigation include: minimizing impact to existing waterways and other natural environments, minimizing project right-of-way impacts, project schedule impacts, cost, and temporary stability of landslide masses during construction of mitigation elements.

In areas where the highway alignment crosses regional, ancient landslide complexes, design emphasis was placed on stabilization of local landslide features immediately impacted by highway construction and not on stabilization of the larger, ancient features.

Due to the presence of multiple failure zones at varying elevations within many of the landslide features (nested shears), mitigation designs employing shear keys have incorporated staged-excavation-and-backfill sequences to minimize the potential for moderate to large-scale failures during construction. The shear key cut slopes are continually monitored during construction for movement using dedicated instrumentation (see Construction Monitoring below). The generalized sequence for shear key construction is shown on Figure 5 and outlined as follows:

**Stage 1** excavations are advanced to elevations approximately 3–4.5 m (10–15 ft) above the interpreted upper landslide failure surfaces (usually defined by a contact between upper SDC deposits and highly disturbed landslide block material (WRSD) composed of highly to moderately weathered Tyee sandstone and siltstone). Stage 1 can be excavated in 90 m (300 ft) wide cuts (approximately perpendicular to assumed landslide movement direction).

←

Figure 4. Schematic concept of landslide development. (A) Flexural slip (intrastratal slip) along bedding planes in the Tyee Formation during tectonic tilting and uplift. (B) Uplift with erosion into bedrock and initial translational-block landsliding develops along bedding. (C) Uplift continues with deeper erosion and resultant deeper translational-block landslides. (D) Groundwater lowering (due to drier Holocene climate) and landslide activity diminishes.

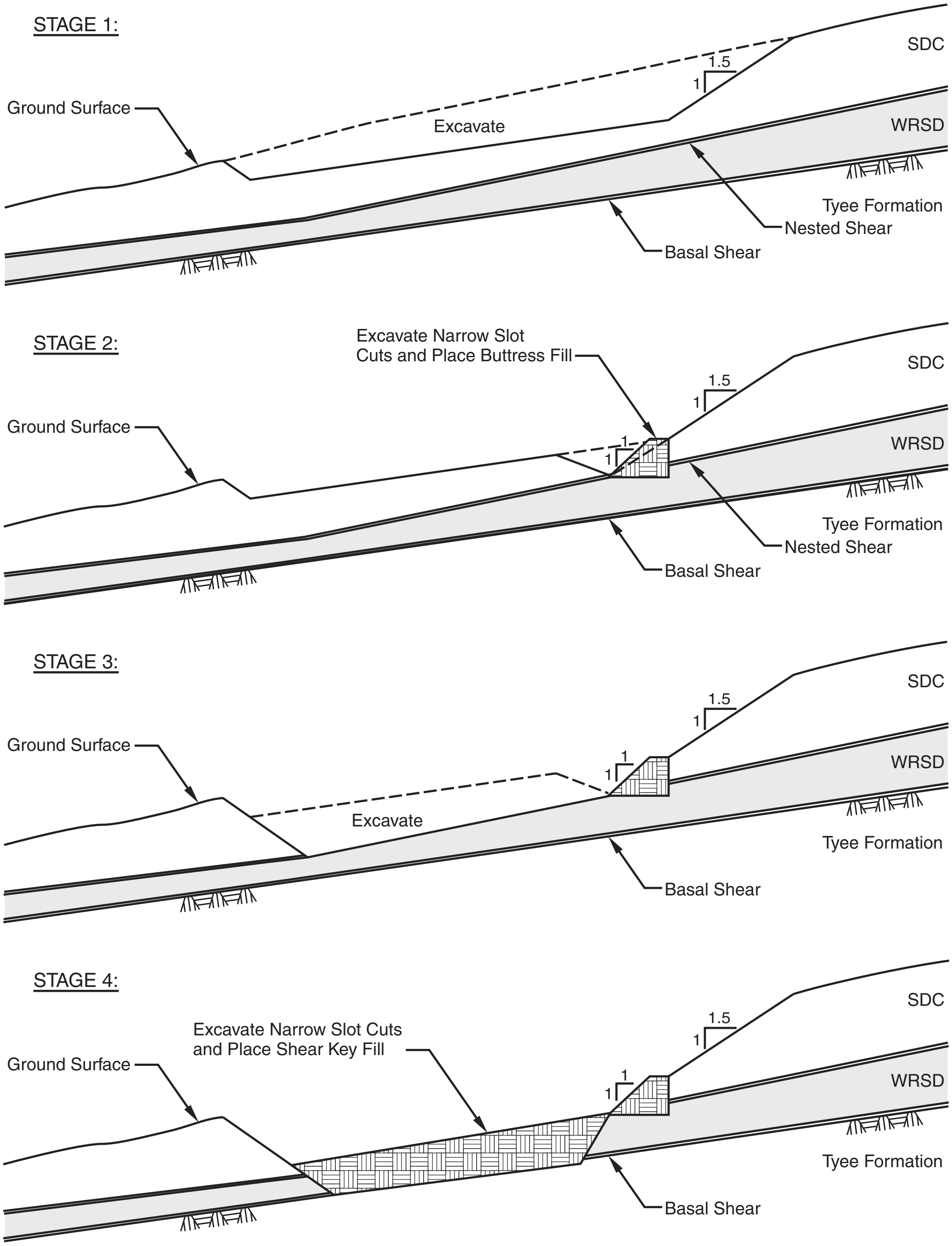


Figure 5. Generalized shear key construction sequence shown in cross section. SDC—slide debris/colluvium; WRSD—weathered rock slide debris.

**Stage 2** is designed to remove the upper failure surfaces and place a small buttress to establish temporary stability of the upper slide masses. This work is performed in narrow slot cuts that are 3–6 m (10–20 ft) wide to minimize lateral exposure of the shear zone(s). The buttresses can be constructed from common site fill material, which requires significant compactive effort using specialized equipment. Alternatively, on-site shot rock (Tyee Formation sandstone) or imported stone embankment material can be placed with less compaction effort, which decreases the amount of time needed to complete Stage 2.

**Stage 3** excavations remove the lower landslide block material to elevations approximately 3–4.5 m (10–15 ft) above the basal shear zone, generally defined by slickensided, clayey zones associated with Tyee Formation bedding. As with Stage 1, Stage 3 can be excavated across 90 m (300 ft) wide cuts.

**Stage 4** is designed to remove the lower shear zone and establish the bottom of the shear key. The Stage 4 excavations are performed in 6 m (20 ft) wide slot cuts to minimize lateral exposure of the basal landslide shears. Following excavation of each slot cut, select backfill material is placed and compacted back to the initial Stage 4 elevations prior to excavation of succeeding slots.

Following completion of Stage 4, cut-off drainage trenches are established along the uphill edge of the shear key bottom to relieve groundwater pressure in the remaining slide mass upslope from the shear key. The trenches are excavated to penetrate the basal landslide shear and backfilled with drain rock wrapped in filter fabric. The shear key is then backfilled with on-site source, select embankment material to approximate original grade.

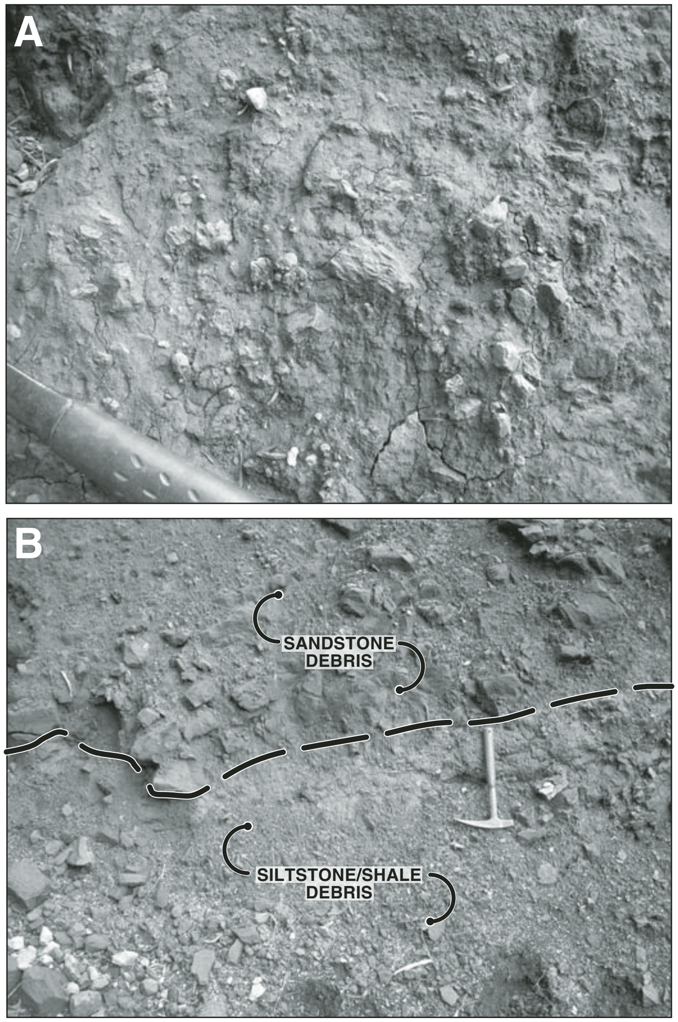


Figure 6. (A) Slide debris/colluvium (SDC) in the Crystal Creek landslide that is completely disturbed. (B) SDC that is partially disturbed and/or dilated and retains stratigraphic separation within the debris of the Crystal Creek landslide. Photos by Charlie Hammond.

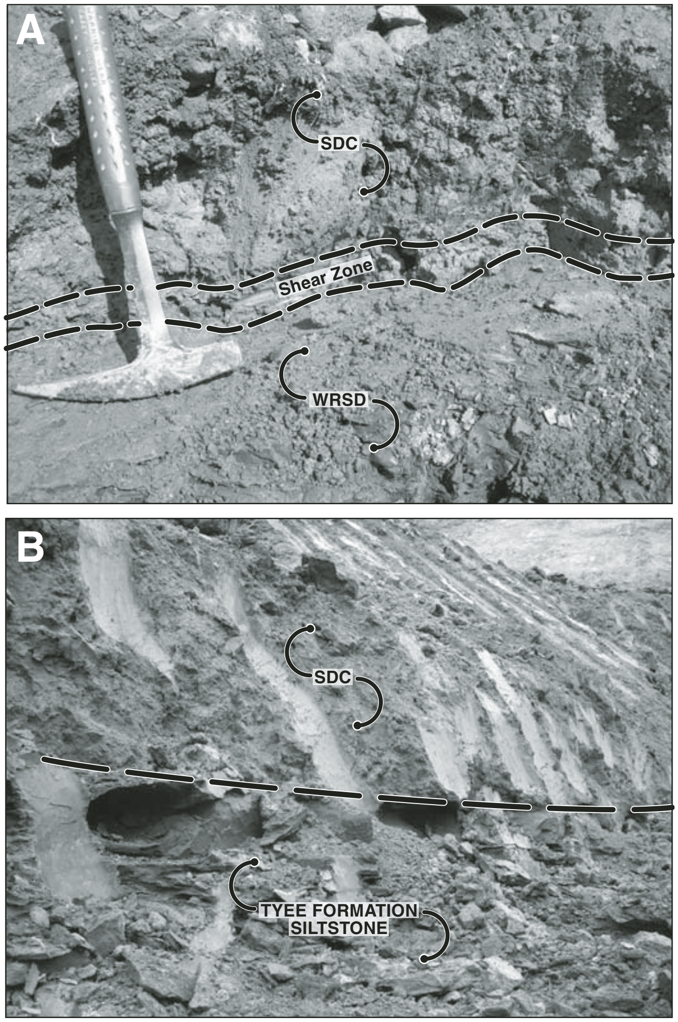


Figure 7. (A) Shear zone at base of slide debris/colluvium (SDC) and top of the weathered rock slide debris (WRSD)–bedded unit in the Eddy Creek Tributary C & D landslide. Photo by Charlie Hammond. (B) Shear zone at base of SDC and top of Tyee Formation siltstone bedrock in the Cougar Creek landslide shear key. Photo by Dan Meier.

Several road cuts, up to 60 m (200 ft) high, are necessary along the alignment. The cut slopes utilize variable final slope angles, based on the expected material properties associated with the soil, weathered rock, and fresh rock encountered within the cut slope section. The cut slope angles vary from 1.5H:1V in colluvium and topsoil, to 1H:1V in weathered Tyee Formation rock, to 0.5H:1V in fresh Tyee Formation Rock.

In some locations, the upper portions of the cuts have exposed preexisting, ancient landslide failure surfaces, often associated with the base of the weathered rock. Removal of the cut material has locally destabilized the toe regions of the landslides, resulting in partial failures that are 6–30 m (20–100 ft) wide.

Interpreted extent of the paleo-landslide deposits often includes large areas that extend well outside of project right of way. Mitigation of the entire slide mass is generally impractical, due to the regional nature of the features. The contract team has designed and constructed shear keys and buttresses that are sized to stabilize the areas of the paleo-landslides that are involved in construction. The intent is to prevent failure of the lower 30 m (100 ft) of the slide mass and arrest propagation of the failure upslope into the larger paleo-landslide.

## Construction Monitoring

Slope inclinometers have been used to monitor for ground movement. In general, the majority of the instruments showed no movement of the landslide terrain during the 2007–2008 wet season. However, six instruments recorded creeping landslide movement up to 2.5 mm (0.1 in) per month, with four of those stopping at the end of the wet season. Two of the instruments continued

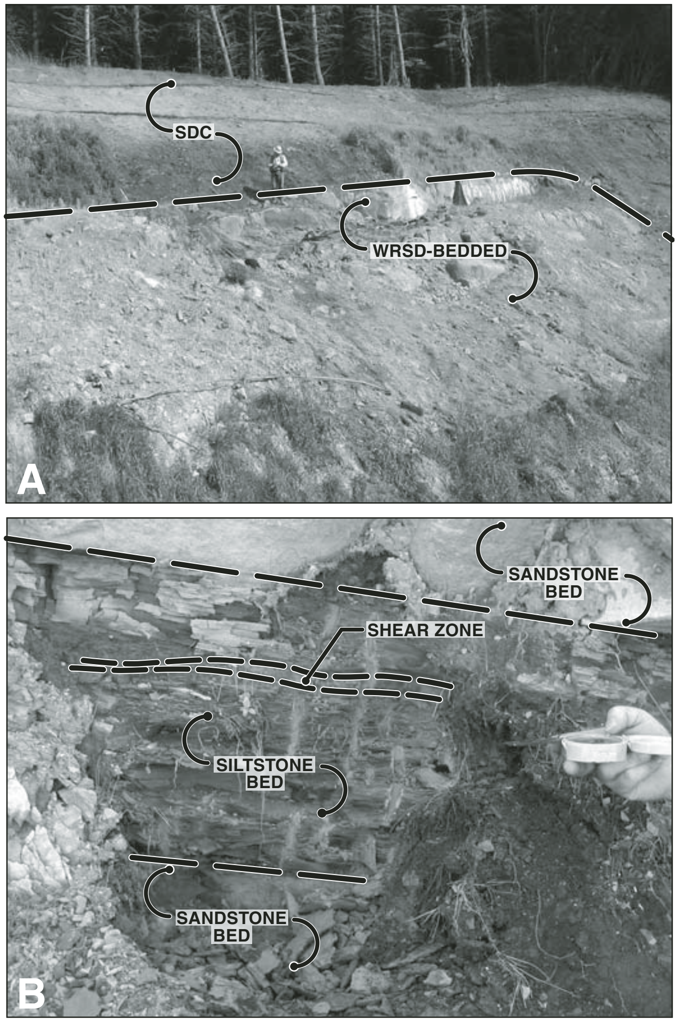


Figure 8. (A) Slide debris/colluvium (SDC) overlying weathered rock slide debris (WRSD)–bedded in the Eddy Creek Tributary C & D landslide. (B) Shear zone in the Cougar Creek landslide within a siltstone bed of WRSD-bedded. Photos by George Machan, Landslide Technology.

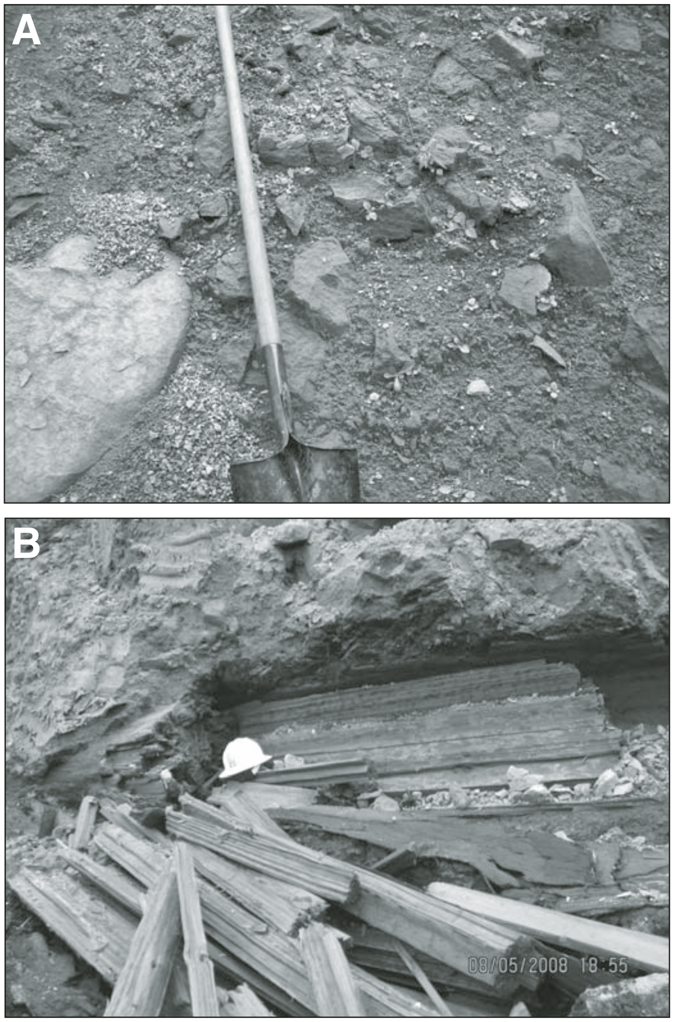


Figure 9. (A) Weathered rock slide debris (WRSD)–intermixed in the Eddy Creek Tributary C & D landslide. Photo by Charlie Hammond. (B) Ancient log entombed in WRSD-intermixed in the Eddy Creek Tributary C & D landslide. Photo by Eric Knapp, Oregon Department of Transportation.

to record creep movement during the summer, likely due to construction grading prior to installation of the instruments.

In addition to seasonal movement, landslide movement was monitored specifically for construction of shear keys using in-place inclinometer (IPI) strings placed in boreholes located near the tops of the shear key excavation cut slopes. Each IPI string contains up to 5 individual micro-electro-mechanical sensor (MEMS) inclinometer probes, which are connected to a central data logging device and telemetered to a dedicated computer to record and display movement within the inclinometer strings in real time. If excessive movement is detected in one or more IPI strings, excavation can be suspended, temporary stability can be reestablished, and the construction sequence reevaluated.

To date, shear keys have been constructed at the Cougar Creek landslide (Fill 10) and the Eddy C/Eddy D landslide (Fill 4). Figure 11 presents a time history during construction of the Cougar shear key of movement recorded in three IPI strings. The data indicates a spike in slide movement on the upper shear zone during the second stage of excavation, with subsequent cessation of activity following backfill of the shear key and establishment of the buttressing mass.

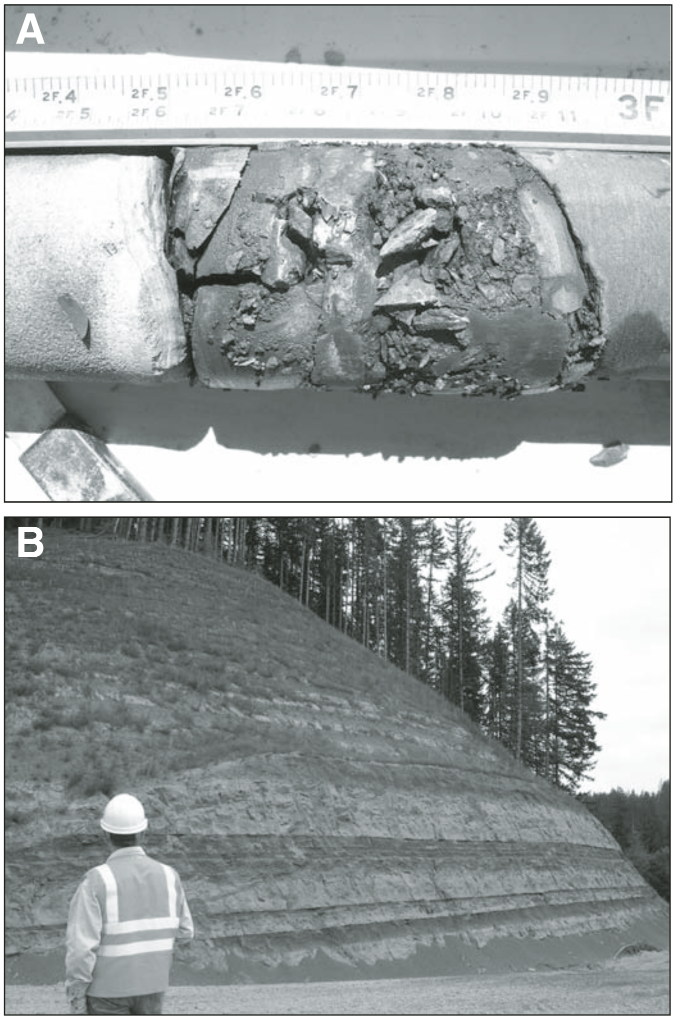


Figure 10. (A) Basal landslide shear zone (crushed siltstone) in core sample from the Crystal Creek landslide. Photo by Chris Carpenter, Landslide Technology. (B) Tyee Formation bedrock in a road cut at the east end of the project. Photo by George Machan, Landslide Technology.

## STOP 1. PROJECT CONSTRUCTION OFFICE

Stop 1 will be at the project construction office to overview the field trip objectives, geology, geotechnical monitoring and construction, and to preview the field trip guide/handouts.

## STOP 2. SHEAR KEY IN THE TOE OF GIANT EDDY CREEK TRIBUTARY C AND D LANDSLIDE

Stop 2 is the toe of a giant landslide complex where an embankment shear key is being constructed. Organic materials collected from slide debris in a shear key excavation were radiocarbon tested at 17,850 ± 100 and 29,820 ± 100 yr B.P. Ground movement and groundwater pressures have been monitored around the shear key prior, during, and post-construction. An embankment will eventually bury the shear key.

## STOP 3. MARGIN OF GIANT EDDY CREEK TRIBUTARY C AND D LANDSLIDE (CUT 4)

Stop 3 is the margin of a giant, deep-seated landslide complex that abuts against undisturbed Tyee Formation bedrock. The highway through-cut exposes the bedrock and WRSD, which appears to have buried a paleo-forest at this site, pieces of which have been radiocarbon tested at >46,400 and 40,920 ± 570 yr B.P. Since the cut was excavated, it has experienced local movement of rock blocks and SDC.

## STOP 4. GIANT EARTHFLOW AT EDDY CREEK TRIBUTARY A AND B

Stop 4 is on the eroded remnants of a giant earthflow that has been radiocarbon dated at 36,850 ± 380 yr B.P. Local drainages have incised the earthflow debris to depths of 21 m (70 ft), and have eroded and completely removed the head of another giant landslide complex that lies to the west, the Crystal Creek landslide. Recent landslide activity in the area has included local slumps and sloughing of SDC. This is the site of the Eddy "B" Bridge that has tall approach-embankments that bury portions of the valleys.

## STOP 5. DRAINAGE DIVIDE BETWEEN EDDY CREEK TRIBUTARY A AND CRYSTAL CREEK (CUT 5)

Cut 5 was excavated through the giant, deep-seated Crystal Creek landslide. The road cut exposes colluvium that buries an eroded paleo-scarp. Wood collected from a clay lens buried by the colluvium was radiocarbon tested at >40,000 yr B.P.

TABLE 1.

| Sample location | Radiocarbon age (yr B.P.) |
|---|---|
| Eddy Creek Tributary C & D Landslide Complex: organic sediment collected in drill hole F5-03, 25 feet above base of giant translational slide (F503-R14)* | 40,920 ± 570 |
| Eddy Creek Tributary A & B drainages: organic sediment collected in drill hole F6-04, 15 feet above base of giant ancient earthflow (F604-R12)* | 36,850 ± 380 |
| Eddy Creek Tributary C & D Landslide Complex: wood core-sampled in drill hole C4BH05-1, ~2 feet above base of giant translational slide (No. 19)** | >46,400 |
| Eddy Creek Tributary C West Side: wood excavated from Cut 4 at margin of giant translational landslide (C4-C14-1)*** | >40,000 |
| Eddy Creek Tributary C & D Landslide Complex: wood excavated from the east end of a shear key through an ancient earthflow slide (ECSK-C14-2)*** | 17,850 ± 100 |
| Eddy Creek Tributary C & D Landslide Complex: wood excavated from the approx. middle of a shear key through the toe of giant slide (ECSK-C14-2)*** | 29,820 ± 100 |
| Crystal Creek Landslide Graben: wood excavated from Cut 5 and a clay lens in an ancient slide graben (C5-C14-1)*** | >40,000 |
| Cougar Creek Landslide Complex: wood excavated from the Cougar Creek shear key within toe of giant landslide (CCSK-C14-1)*** | 38,830 ± 860 |

*Cornforth Consultants (2008); atomic mass spectrometry (AMS) technique.
**URS (2006); AMS technique.
***URS (p.c., 2008); radiometric technique.

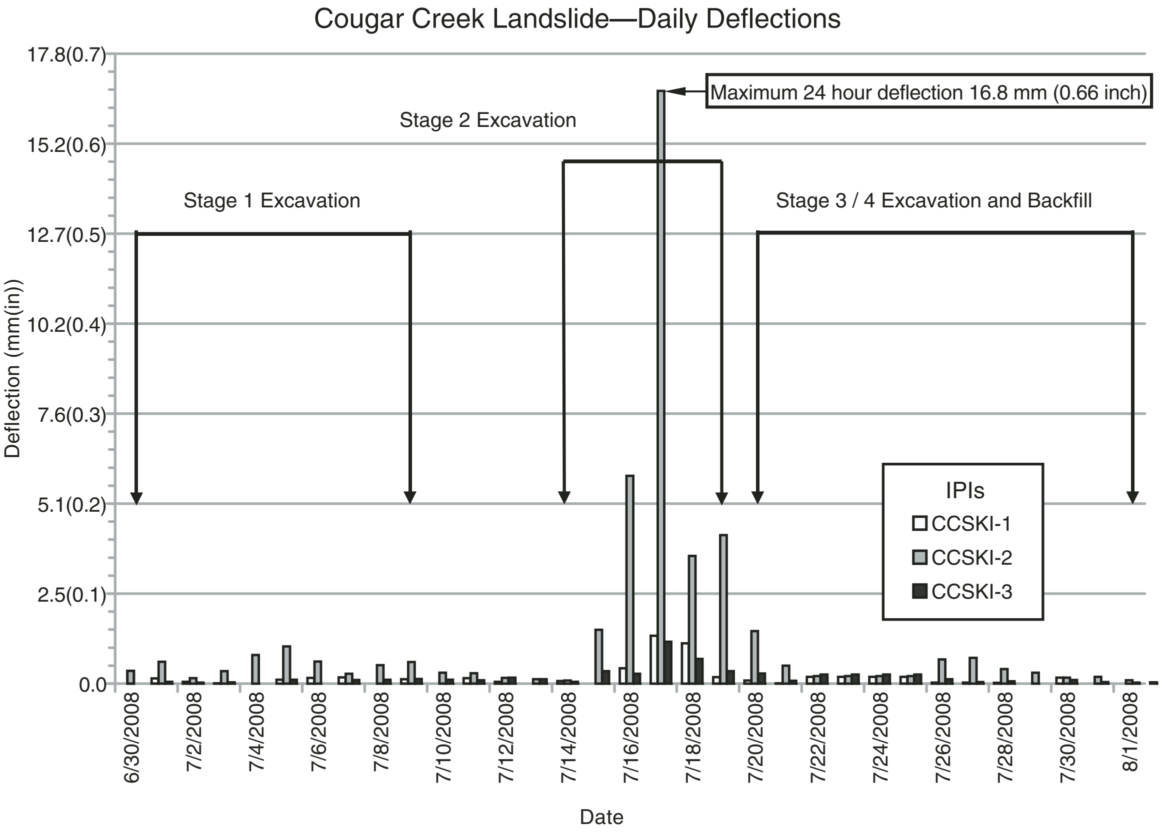


Figure 11. Daily deflections measured with In-Place Inclinometers (IPIs) during construction of the Cougar Creek landslide shear key (CCSKI).

The drainage divide is also the site of a previously unmapped, northwest-southeast–trending, high-angle fault that forms the northeast lateral margin of the Crystal Creek landslide. The fault was uncovered by the excavation of the through-cut, and it contributed to a local cut slope failure during construction.

## STOP 6. CRYSTAL CREEK–COUGAR CREEK DIVIDE

This stop will be the new pass over the coast range. Through-cuts expose the Tyee Formation overlain by relatively shallow translational block landslides, which are being mitigated with buttresses.

## STOP 7. COUGAR CREEK SLIDE AND SHEAR KEY

Stop 7 is on the Cougar Creek slide, which is a deeply eroded translational block slide. To minimize potential reactivation of landslide movement, caused by loading of the slide from a highway embankment, a shear key was constructed through the slide debris. Excavation for the shear key exposed the paleo-drainage that had been buried by the landslide. The embankment is the east approach to the Cougar Creek bridge.

## STOP 8. BIG SLIDE AND BOX SLIDE

Based on landslide morphology, Stop 8 is at two of the youngest, deep-seated landslides along the project (no radiocarbon samples to date). Although appearing to have moved recently, and also having the highest groundwater levels in all of the slides, slope inclinometers have not shown landslide movement to date.

Note: The above list of eight stops is subject to change due to weather and construction schedule.

## ACKNOWLEDGMENTS

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