Geologic Resources Inventory Scoping Summary Lewis and Clark National and State Historical Parks, Oregon and Washington

Prepared by John Graham
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Geologic Resources Division
National Park Service
US Department of the Interior

The Geologic Resources Inventory (GRI) provides each of 270 identified natural area National Park System units with a geologic scoping meeting and summary (this document), a digital geologic map, and a Geologic Resources Inventory report. The purpose of scoping is to identify geologic mapping coverage and needs, distinctive geologic processes and features, resource management issues, and monitoring and research needs. Geologic scoping meetings generate an evaluation of the adequacy of existing geologic maps for resource management, provide an opportunity to discuss park-specific geologic management issues, and if possible include a site visit with local experts.

The National Park Service held a GRI scoping meeting for Lewis and Clark National and State Historical Parks (LEWI) on October 14, 2009 at Fort Clatsop Visitors Center, Oregon. Meeting Facilitator Bruce Heise of the Geologic Resources Division (NPS GRD) introduced the Geologic Resources Inventory program and led the discussion regarding geologic processes, features, and issues at Lewis and Clark National and State Historical Parks. GIS Facilitator Greg Mack from the Pacific West Regional Office (NPS PWRO) facilitated the discussion of map coverage. Ian Madin, Chief Scientist with the Oregon Department of Geology and Mineral Industries (DOGAMI), presented an overview of the region's geology. On Thursday, October 15, 2009, Tom Horning (Horning Geosciences) and Ian Madin (DOGAMI) led a field trip to several units within Lewis and Clark National and State Historical Parks.

Participants at the meeting included NPS staff from the park, Geologic Resources Division, and the Pacific West Regional Office and cooperators Tom Horning (Horning Geosciences), Ian Madin (DOGAMI), and Colorado State University (CSU) (see table 2). This scoping summary highlights the GRI scoping meeting for LEWI including the geologic setting, the plan for providing a digital geologic map, a discussion of geologic resource management issues, a description of significant geologic features and processes, and a record of meeting participants.

Park and Geologic Setting

Dedicated in 2004, Lewis and Clark National and State Historical Parks are administered through a cooperative venture involving the National Park Service and the states of Oregon and Washington. The park consists of 12 sites located along a 64-km (40-mi) stretch of the Pacific coast from Long Beach, Washington to Cannon Beach, Oregon, and commemorates key aspects of the Corps of Discovery's expedition during the winter of 1805-1806.

Volcanic rocks of the Eocene [55.8-33.9 million years ago (mya)] Crescent Formation are the oldest rocks in the Cape Disappointment area of southwestern Washington. The Crescent Formation formed as a chain of seamounts (submarine volcanoes) in the Pacific Ocean basin. Active subduction of the Pacific Plate beneath the North American Plate eventually caused the seamounts to collide with the western continental margin of North America. The Crescent Formation contains submarine-pillowed, columnar jointed and massive basalt flows (Wells 1989).

South across the Columbia River, younger, Miocene-age (23.03-5.332 mya), marine sedimentary rocks of the Astoria Formation anchor the city of Astoria (Niem et al. 1985). The east-west trending fault that separates the older rocks in southwestern Washington from the younger rocks in northwestern Oregon lies beneath the Columbia River. Inland along the Lewis and Clark River, a tributary to the Columbia River, the Corps of Discovery constructed Fort Clatsop on top of the Upper Eocene mudstones and siltstones of the Smuggler Cove Formation. Now exposed at the surface, these sediments were originally deposited in deep marine environments. Originating in the plateau country of eastern Oregon and Washington, Miocene basalt flows of the Columbia River Basalt Group form the impressive Tillamook headland upon which Ecola State Park is located (Niem et al. 1985; Niem and Horning 2006; Wells et al. 2009).

The Tertiary exposures are overlain by a variety of Quaternary deposits including shoreline sediments; fluvial, terrace, and estuarine deposits; and landslide material. Current depositional environments from Long Beach to Cannon Beach include sand spits, beaches, elongate sand dunes, and low swales containing ponds or peat bogs. Old beach ridges that run parallel to the coast mark past positions of the shoreline as the influx of new sand built the beach seaward. Today, dams along the Columbia River trap most of the sediment before it reaches the coast.

The mouth of the Columbia River presents a unique estuarine/fluvial system within the active tectonic margin of western North America. Major geologic structures in the region consist of folded and faulted, north- to northwest-trending basement uplifts. Reverse faults bound the western margins of the uplifts and tectonic reconstructions suggest that the entire region has undergone significant clockwise rotation (Wells et al. 1998; McCaffrey et al. 2007). Earthquakes generated from the subduction of the Pacific Plate beneath the North American Plate continue to produce landslides and tsunamis that may impact northwestern Oregon, southwestern Washington, and the units within Lewis and Clark National and State Historical Parks.

LEWI geology and issues (Ian Madin)

Ian Madin's (DOGAMI) overview focused on the following topics:

- Geologic Framework
- Regional Geology of Washington and Oregon
- LIDAR and Surficial Geology
- Landslides
- Coastal Change
- Tsunamis
- Cascadia Earthquakes

Geologic Framework

Three world-class events define the geologic framework of Washington and Oregon: 1) subduction, 2) Columbia River basalts, and 3) glaciation. For the past 50 million years, the subduction of oceanic crust beneath the North American continent has dominated the geologic framework in the region. Three primary features characterize the subduction zone: an offshore trench, a subduction fault, and a volcanic arc. The Cascade Range is the most recent in a series of volcanic arcs associated with subduction. Between the Cascades and the offshore trench lies a forearc basin (a basin that forms seaward, or in front of, the volcanic arc) where seafloor sediments harden into rock. Western Oregon between the Cascade Range and the coast consists of forearc sedimentary strata that have since been deformed and accreted to the continental margin.

The Columbia River Basalts represent the second world-class event. About 16 mya, giant lava flows, known as flood basalts, from gigantic fissures where Oregon, Washington, and Idaho intersect. A recent University of Oregon study suggests that lava flowed from the area of Pullman, Washington down the Columbia River valley to the ocean in just 7 days. In a unique process, basaltic lava flowed 560 km (350 mi) over land then flowed out to sea where the lava burrowed into the sediment for another 50 km (30 mi), from the mouth of the Columbia River valley, nearly to the subduction zone. The term, "invasive lava," has been coined to describe this unique process, and similar flows are found as far south as Newport, Oregon. At least 20 times, enormous lava flows about 30 m (100 ft) deep and 480 km (300 mi) long filled the Columbia River valley and entered the ocean near Astoria.

The third world-class event to affect western Oregon and Washington was the Pleistocene Ice Age. About 12,000 years ago, the coast lay 80 km (50 mi) offshore relative to today's coastline. As the glaciers melted and sea level rose, the Columbia River valley filled with water and sediment. Today's coastal landforms such as dune ridges, spits, beaches, and estuaries, therefore, are extremely recent features.

Regional Geology

A regional stratigraphy consisting of marine sedimentary rocks, lava from the Columbia River basalt, and young Quaternary deposits resulted from these three world-class events. In Washington, a regional unconformity separates Quaternary deposits from the middle Miocene Columbia River Basalt Group (CRBG) and the Eocene tuffs and basalts. In Oregon, 20 mya Oligocene-Miocene rocks represent the oldest deposits. A fault juxtaposes the older rocks in Washington with the younger Oregon strata. Park units in Oregon sit atop the zone where CRBG lava is transitional from subaerial to invasive.

LIDAR and Surficial Geology

LIDAR (Light Detection and Ranging) remote sensing provides essential data for accurate surficial geologic mapping (fig. 1). The technique strips away the Pacific Northwest's dense vegetation to expose the underlying surface geology. LIDAR data, which is available for the LEWI region, also illuminates landslide scarps and slumps in stark detail and could provide an excellent base map for surficial mapping.

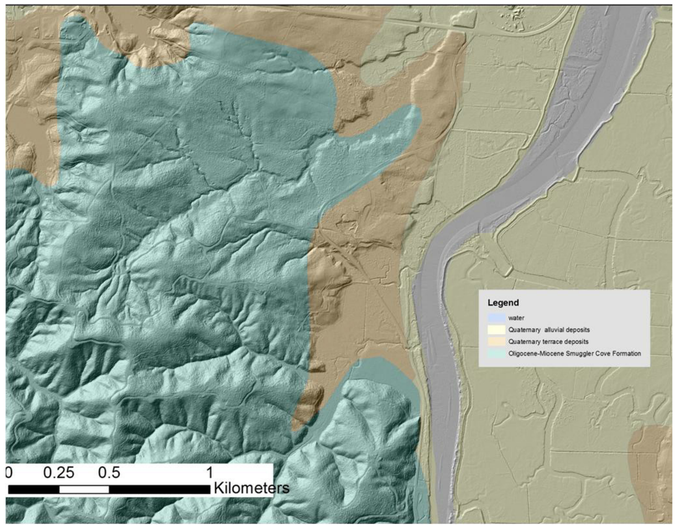

Figure 1. LIDAR data illustrates the imperfections in current surficial mapping and the need to redefine the contacts between surficial units. In this example, courtesy of Ian Madin, the colors represent individual surficial units mapped without using LIDAR overprinted on a LIDAR base map. Notably, the contact between the green and brown units is inaccurate. Although originally mapped both within the topographic slope and in the valley, the contact should be at the base of the topographic slope where the river valley begins.

Landslides

Northwest Oregon is one of the most landslide prone areas in the world. The current wet cycle coupled with subduction zone earthquakes creates a high landslide potential for the region. LIDAR maps show the hills of Astoria composed primarily of landslide deposits (fig. 2). The landscape of Ecola State Park is dominated by landslides and slumps. Because LIDAR provides detailed topographic contours, landslide movement and head scarps can be identified in greater detail. For example, debris flow geometry at the mouth of tributaries may be missed using conventional mapping. Using LIDAR, these debris flows may be accurately mapped and upslope landslides identified.

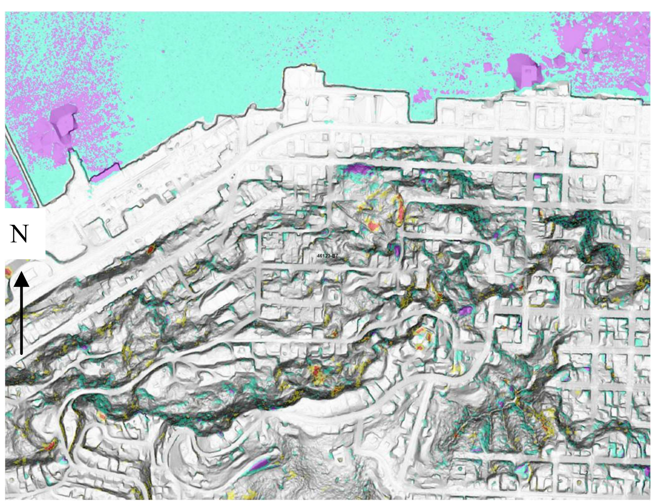

Figure 2. Landslides, indicated by the rumpled topography, inundate the landscape in this LIDAR image of Astoria, Oregon, courtesy of Ian Madin (DOGAMI).

Coastal Change

Sea level change is not as important along the northern Oregon coast as is the increase in wave height and frequency of storm events. Over the last 30 years, the size of storms and accompanying storm waves has dramatically increased. In the past, a 9 m (30 ft) storm wave was considered exceptionally large, but today, storm waves may reach a height of 12-14 m (40-45 ft), significantly increasing the potential for massive erosion. The typical 100-year wave of the past now occurs approximately every 10 years.

Both beach erosion and accretion occurs along the coast. The Oregon Department of Geology and Mineral Industries (DOGAMI) and the Northwest Association of Networked Ocean Observing Systems (NANOOS) have been monitoring coastal change for several years. Monitoring at numerous sites along the coast includes documenting the shape and elevation of the beach as well as recording erosion or accretion of the beach.

Tsunamis

Submarine earthquakes related to the Cascadia Subduction Zone may produce tsunamis, which pose a significant hazard to communities along the northern Oregon coast. Modeling a worst case scenario, a tsunami produced by a magnitude 9.5 Cascadia Zone earthquake would arrive at the coast in 10 minutes. A potential 24 m (80 ft) wave would sweep over Canon Beach and a 17 m (56 ft) wave would drown Astoria. Examples from the 1964 tsunami that came ashore at Seaside, Oregon were discussed during the fieldtrip on Thursday and documented below.

Cascadia Zone Earthquakes

The Cascadia Subduction Zone extends from Vancouver Island to Cape Mendocino, California. The 1,000 km (620 mi) subduction zone is one of the world's largest. In the last 10,000 years, 20 major earthquakes have occurred along the Cascadia Subduction Zone. Seismic activity along Oregon's portion of the subduction zone produced a magnitude 9.5 earthquake in January, 1700. Cores taken form turbidite deposits provide an historic record of giant earthquakes off the coast of Oregon, and suggest that earthquakes with magnitudes from 8.5 to 9.2 recur at an average of 460 years. There is a 15% chance that a large earthquake along the Oregon coast will occur in the next 30 years. In an earthquake cycle, centuries of uplift and tree growth are followed by minutes of subsidence triggered by the earthquake and inundation of coastal areas due to subsidence.

Geologic Mapping for Lewis and Clark National and State Historical Parks

During the scoping meeting, GIS Facilitator Greg Mack (NPS PWRO) showed some of the main features of the GRI Program's digital geologic maps, which reproduce all aspects of paper maps, including notes, legend, and cross sections, with the added benefit of being GIS compatible. The NPS GRI Geology-GIS Geodatabase Data Model incorporates the standards of digital map creation for the GRI Program and allows for rigorous quality control. Staff members digitize maps or convert existing digital data to the GRI digital geologic map model using ESRI ArcGIS software. Final digital geologic map products include data in personal MS Access geodatabase and shapefile formats, an ESRI ArcMap map document with feature class symbology, feature class layer files, FGDC-compliant metadata, and a help file in Adobe PDF format. The help file captures available ancillary map data including unit descriptions, source citations, ancillary map graphics, correlation of map units, cross sections, and geologic report. The help file can be accessed directly from the map document or using MS Windows Explorer. Final data products are posted at http://science.nature.nps.gov/nrdata/. The data model is available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm.

When possible, the GRI Program provides large scale (1:24,000) digital geologic map coverage for each park's area of interest, which is often composed of the 7.5-minute quadrangles that contain park lands (fig. 3). Maps of this scale (and larger) are useful to resource managers because they capture most geologic features of interest and are spatially accurate within 12 m (40 ft). The process of selecting maps for management begins with the identification of existing geologic maps and mapping needs in the vicinity of the park. Scoping session participants then select appropriate source maps for the digital geologic data (table 1) or develop a plan to obtain new mapping, if necessary.

Table 1. GRI Mapping Plan: Best Available Map Coverage for LEWI

Covered Quadrangles	GMAP[1]	Citation	Scale	Format	Assessment	GRI Action
State map: Washington side	74832	Washington Division of Geology and Earth Resources staff. 2008. Digital geology of Washington State. Scale 1:100,000. On-line GIS data, version 2.0.	1: 100,000	Digital	On-line data	Possibly use this map
State map: Oregon side		Ma, L., I.P. Madin, K.V. Olson, and R.J. Watzig, R. E. Wells, A. R. Niem, G. R. Priest . 2009. Oregon Geologic Data Compilation Release 5 (Statewide) OGDC-5. Portland, OR: Oregon Department of Geology and Mineral Industries..		Digital	On-line data	Available on DVD.
Tillamook Head	75199	Niem, A. R. and Niem, W. A. In preparation. Geologic map of the Tillamook Head 7.5' quadrangle, Oregon. Scale 1:24,000. Open-File Report. Reston, VA: U.S. Geological Survey.	1:24,000	Digital?	No deadline for completion.	None.

[1]GMAP numbers are unique identification codes used in the GRI database.

Lewis and Clark National and State Historical Parks contain 21 quadrangles of interest (fig. 3). The quadrangles capture the watersheds that surround the park units. Professor emeritus Alan Niem is diligently mapping the Warrenton, Astoria, Cathlamet Bay, Gearhart, Olney, and Green Mountain urban corridor quadrangles for the U.S. Geological Survey (USGS), but it is doubtful that he will complete the maps within a timeframe beneficial to the park. Oregon compilation map OGDC-5 (Ma et al. 2009) was recently completed and compiles data from both surficial and bedrock maps with a variety of source map scales. LIDAR has shown that about 30% of the unit contacts on the existing maps are incorrect and about 90% of the landslides haven't been mapped properly. LIDAR data that may be used to re-delineate the contacts and map the landslides will be available for purchase at the end of 2009.

DOGAMI completed a coastal erosion map for Clatsop County in 2009 that includes a detailed, 1-km (0.6-mi) wide, coastal strip map. When published, the map will include GIS and extend from the mouth of the Necanicum River to Newport, Oregon. North of the Necanicum River the coast changes from an erosional coastline to an accreting coastline.

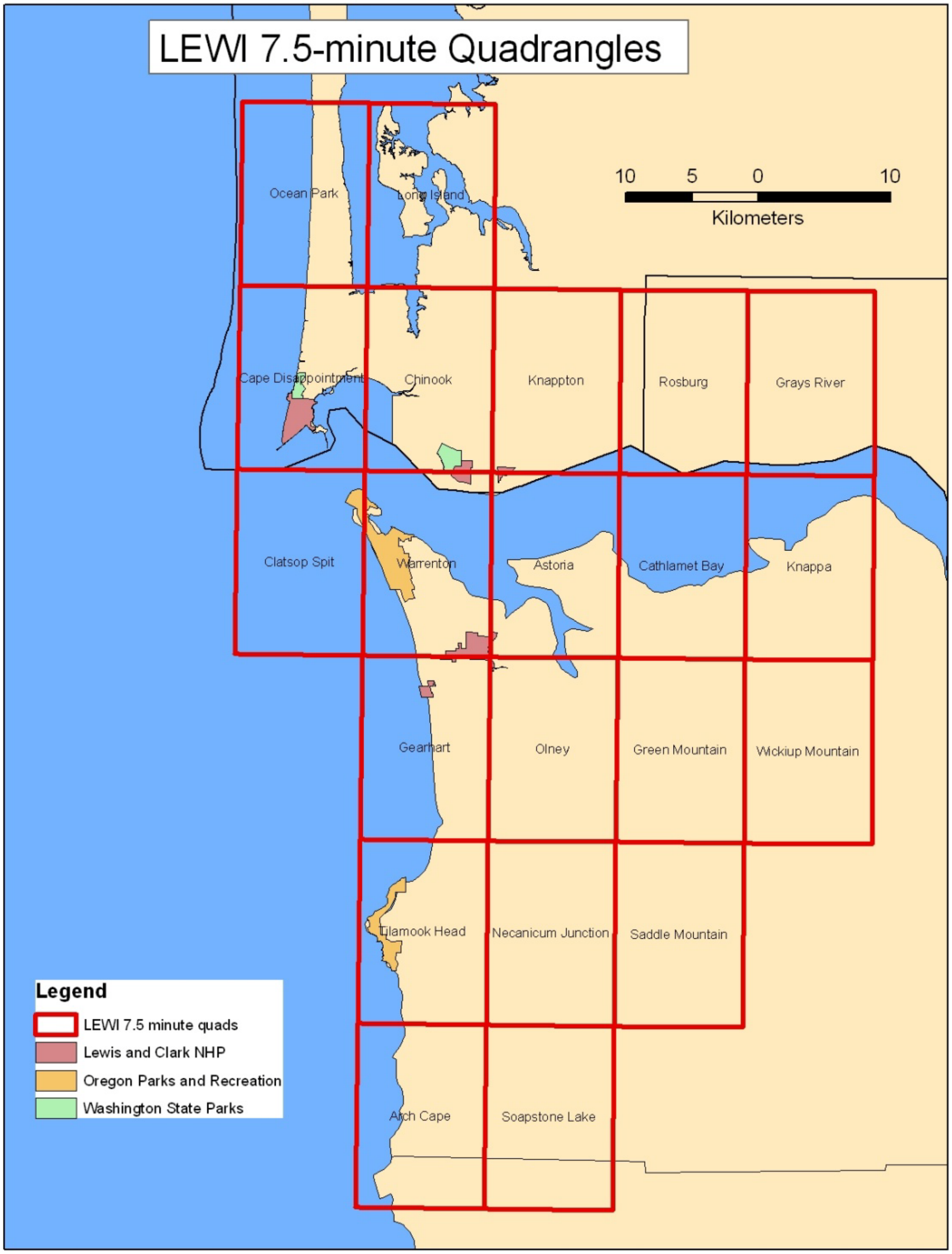

Figure 3. Quadrangles of interest for Lewis and Clark National and State Historical Parks, Oregon and Washington.

Participants decided to follow a mapping priority as follows:

1. Use what's available with the understanding that changes will be made.
2. Acquire LIDAR and use the data to re-delineate the surficial geology. This option requires funding.
3. Wait for the USGS to finish mapping and their review of the finished map. Subsequent communication from Dr. Ray Wells, the USGS geologist responsible for mapping in the area north of the Columbia River, suggests these data may be available shortly. An email from Dr. Wells dated 11-2-2009, reads: "The geology of the north side of the Columbia River is published (not several years out). Note also that we recently compiled it all digitally in ArcGIS on 24 K bases. The first digital file (Willapa Hills) should be released momentarily, as soon as metadata are completed. Grays River and Cape Disappointment are not far behind." Heise will follow up with Dr. Wells to determine when that data might become available.

Geologic Resource Management Issues

The principal geologic resource management issues discussed during the scoping session and on the subsequent field trip included coastal issues, mass wasting, earthquakes and tsunamis resulting from seismic activity, and issues associated with changing climate. Other potential geologic resource management issues involve interdunal lake evolution due to rising sea level, minor seasonal flooding, and interpretive displays at Ecola State Park.

Coastal Issues

Historically, dune growth along the northern Oregon coast has occurred at a rate of 0.6 to 0.9 m (2 to 3 ft) per year. Beginning around 1880, the Army Corps of Engineers (Corps) installed north and south jetties at the mouth of the Columbia River and dammed rivers that supply sediment to the coastline. When the jetties were built, sand flushed from the lower estuary into the ocean and accelerated beach and dune growth. Westward expansion of beaches increased up to 14 m (45 ft) per year but has since diminished to approximately 2 to 4 m (6 to 12 ft) per year on Clatsop beaches (Tom Horning, written communication, January 4, 2010).

The Soil Conservation Service (today's Natural Resources Conservation Service [NRCS]) planted invasive Scotch broom, shore pine and non-native beach grasses to stabilize beach dunes and slow the invasion of windblown sand into the grass prairies of Clatsop Plains. While beach progradation has continued regardless of plantings, the vegetation prevented the open sand areas from expanding. The habitat of the dunes changed from an open diverse native prairie to dense monocultures of exotic grasses, scotch broom shrublands and pine forests, thus affecting the natural ecosystem and sand transport along the coast. The transformation of dune environment to pine forest caused the local extirpation of a coastal butterfly.

Jetties and dams have reduced the amount of sand available for natural beach maintenance and promoted both coastal erosion and accretion at different times of the year. In general, long shore drift along the Washington and Oregon coast is dominated by south to north transport in the winter with comparatively minor north to south transport during summer (Tom Horning, written communication, January 4, 2010). Sand trapped in the lee areas of the jetties, such as behind the

North Jetty at Cape Disappointment, contributes to beach accretion. For example, once a sea stack surrounded by water, McKenzie Rock is today surrounded by beach deposits.

Except for these lee areas, the shoreline off Cape Disappointment has retreated nearly 600 m (2,000 ft) since the 1940s (Tom Horning, written communication, January 4, 2010). The high shoreline regression is the result of the northerly directed long-shore current washing away sand from the ebb-tide delta at Peacock Spit (named for the HSS Peacock, which wrecked on July 18, 1841). Coincidently, on board the HSS Peacock was James Dwight Dana, who became the first geologist to set foot in the Pacific Northwest and who later became famous in geological circles. The current beach sand budget is reversed from the early 20th Century sand budget when it favored rapid beach and dune growth. Park management is attempting to persuade the Corps to dump their dredge spoils on the north side of the North Jetty to nourish the beach and retard the rate of beach retreat, but the concept remains controversial because crabbers believe that sand dumping kills crabs and hurts their business.

Mass Wasting

Landslides continually adjust the landscape of northwestern Oregon and southwestern Washington. It's been said that "anything not flat" moves. Landslides and debris flows present potential hazards to the Fort-to-Sea Trail and Station Camp. The Fort Clatsop Visitor Center is constructed an elevated fluvial terrace surrounded by landslides. Although anchored on the basalt of Tillamook Head, Ecola State Park is underlain by surficial deposits that resulted from massive landslides. The Civil War dormitory and lighthouses at Fort Columbia State Park and Cape Disappointment are all at risk.

Seismic Activity

Landslides may occur from weakened soil strength due to water saturation on steep slopes or they may be initiated by earthquakes. Lewis and Clark National and State Parks units lie within a regional tectonic system in which clockwise rotation of the Coast Range is being distributed along both right-lateral and left-lateral strike-slip faults. Compressive forces act in southwestern Washington to produce anticlines (convex folds), synclines (concave folds), and reverse faults, while normal faults result from the extensional forces pulling apart northwestern Oregon. Northwest-southeast trending faults in Oregon and northeast-southwest trending faults in Washington may trigger onshore mass wasting processes such as landslides and slumps.

Offshore earthquakes related to the Cascadia Subduction Zone may generate tsunamis and trigger onshore landslides. The subduction zone lies as far as 130 km (80 mi) offshore, to the toe of the continental slope, but the locked zone may actually reach the coastline. In a worst case scenario, a magnitude 9.5 earthquake could generate 17 m (56 ft) tsunami waves that would inundate all infrastructures, the Plate Boundary Observatory, and the Salt Works in Seaside, Oregon, as well as drown other communities along the coast, including Astoria. Water may rise to perhaps 6 m (20 ft) near Fort Clatsop, which would be approximately 6 m (20 ft) below the elevation of the visitor center (Tom Horning, written communication, January 4, 2010). At Seaside, tsunami waves may be deflected by Tillamook Head and redirected to the north where they may superimpose on other waves, creating mountains of water rather than simply a plateau of water coming ashore. Such an earthquake last occurred in January, 1700. With a recurrence interval of approximately 460 years, another earthquake of that magnitude may be imminent.

Climate Change Issues

As storm intensity increases, landslides and blowdown may destroy trails, roads, and buildings. Sea level rise may increase beach erosion and shorelines may retreat. Rising water tables will alter river and lake processes. Sea level rise may be tempered by a tectonically elevated North American plate caused by subduction of the Oceanic Plate. Units within LEWI may become refugia, allowing plants and animals from a previous time to exist in relatively unchanged habitats.

Interdunal Lakes

Ephemeral ponds in interdune swales may form in winter and disappear in summer. Rising sea level has contributed to a corresponding rise in groundwater tables near the coast so that interdune swales that were previously dry are becoming permanent lakes. A transect inland from the coast records 5 phases of lake evolution within interdune swales. Inland from the coast, swales progress from dry nearest the ocean, intermittent lake, persistent lake, stream connected persistent lakes, and finally, permanent swamp. With rising sea level and groundwater tables, this progression may shift seaward, thus altering current habitat and ecosystem patterns.

Seasonal Flooding

Seasonal flooding may occur on the Lewis and Clark and Youngs rivers. The park is in the process of breaching a dike on the west shore of the Lewis and Clark River, but management does not have plans to remove dikes along the river.

Interpretive Sign at Ecola State Park

An interpretive sign on the Interpretive Trail to Indian Beach in Ecola State Park presents an inaccurate geological interpretation by the Oregon Forest Resources Institute (OFRI). The sign indicates that the subduction zone earthquake in 1700 caused a sudden drop in the coastal plain and knocked down a massive number of trees that subsequently became fuel for a catastrophic fire. In this way, any old growth forest that once grew in the region was long ago destroyed by natural processes of fire, wind and earthquakes. Gravel deposits overlying these charred remains of old growth forest are interpreted by the OFRI as landslide deposits.

However, geologists interpret the stratigraphy differently. A Sitka spruce trunk in a vertical section exposed at Indian Beach dates to 80,000 years ago, not 300 years ago. The buried forest represents a Pleistocene wet period rather than an episode of catastrophic destruction. As sea level rose following the Pleistocene Ice Age, a gravel delta grew over the spruce forest. At the time of the great earthquake of 1700, sea level was lower than today, and the bluff at Indian Beach lay offshore. Shell middens indicate that the terrace was occupied by American Indians by the time the Corps of Discovery arrived to view the beached whale in 1806. Park management may wish to replace this sign with one that is more geologically accurate. In addition, the Clatsop Trail Loop brochure states that "at least three separate forests have come and gone here," misleading the public into believing the bluff has remained static for the past 123,000 years while earthquakes caused all the old growth forests to fall over and burn in massive fires.

Mist Gas Field

According to meeting participants, hydrocarbon exploration poses no immediate management issue, but the Mist Gas Field lies in Columbia County, the county adjacent to the eastern border of Clatsop County. Discovered in 1979, the Mist Gas Field has produced over 1.8 billion cubic meters (65 billion cubic feet) of gas (http://www.oregongeology.org/sub/oil/oilhome.htm, accessed October 2009). No oil is associated with the gas. Heat from invasive basalt flows may have matured the organic matter in buried marine sediments and produced the gas discovered at Mist. Exploration continues, but the generation of gas in the Mist Field from invasive basalt flows may be a unique, and localized process.

Features and Processes

The scoping session for LEWI provided the opportunity to develop the following list of geologic features and processes, which will be further explained in the final GRI report.

Aeolian

- Younger dunes – stabilized by invasive European and east coast beach grasses; dominant feature of landscape between Seaside, Oregon to mouth of Columbia River.
- Older dunes from before 1880 (pre-jetty).
- Coast parallel dune ridges: correlated both north and south of the mouth of the Columbia River.

Coastal

- Sea caves along rocky headlands.
- Beach, back beach, and dune environments (Cape Disappointment, Columbia Beach, Sunset Beach).
- Sea stacks at Ecola State Park.
- Headlands, cliffs.
- Sand spits.
- Extensive and dynamic Columbia River estuary.
- Tide pools.
- Erosion and aggredation processes.
- Jetties.

Caves and Karst

- Sea caves present along rocky headlands.

Fluvial

- Extensive and dynamic Columbia River estuary.
- Natural wildlife island.
- Columbia River continues to aggrade as sediments fill canyon cut during the Pleistocene Ice Age. Liquefaction dikes related to the earthquake in 1700 are now 1 m (3.3 ft) below the surface. Shorelines have aggraded hundreds of feet.
- Exposed liquefaction dikes from the 1700 earthquake on Marsh Island.
- Small streams, some only 5 m (15 ft) wide, are bordered by massive landslide deposits from the Ice Age when streams downcut slopes.
- Tributaries continue to respond to changes to the Columbia River.
- Debris flow deposits recognized by LIDAR at the mouth of tributaries.
- Lewis and Clark River flows through Fort Clatsop.

- Lewis and Clark and Youngs rivers are heavily diked.
- During the Pleistocene Ice Age, tributaries were hanging waterfalls.
- Army Corps of Engineers has armored the Columbia River with riprap; limited concern over flooding.

Hillslope

- Mass wasting (landslides, slumps, debris flow) deposits exist throughout region.

Lacustrine (Lake)

- Interdunal lakes (i.e. Coffenbury Lake).
- Water level in interdunal lakes may rise more than 1.8 m (6 ft) seasonally.
- Lakes formed in shadow zone of jetties (i.e., O'Neil Lake, Swash Lake).
- Man-made lake at Yeon.
- Ecola State Park contained sag ponds before landsliding destroy them. The Ecola parking lot was once a lake.

Seismic

- Evidence of past tsunami activity and sudden, coseismic land level changes in Seaside, OR.
- Potential earthquakes.

Volcanic

- Eocene seafloor lavas (Cape Disappointment and Fort Columbia).
- Columbia River Basalt invasive flows (CRBG) (Ecola State Park).
- In the Dismal Nitch area, submarine basalt and debris flows outcrop at the north end of the bridge (mapped as Crescent Formation or related rocks), and Eocene marine sandstone resting on pillow basalt compose the cliffs behind the rest stop (Ray Wells, U.S.G.S. geologist, written communication, November 24, 2009).
- Pillar Rock (Lewis and Clark campsite) to the east marks the area where subaerial flows of Columbia River Basalt started to get their feet wet as they entered the Columbia River estuary (Ray Wells, U.S.G.S. geologist, written communication, November 24, 2009).

Glacial and Periglacial

- Missoula floods flowed through Columbia River valley to the Pacific Ocean but sea level was much lower.
- Deposits are now submerged and lie beneath the turbidite sequence.

Permafrost

- Gearhart Formation contains sphagnum moss bogs and muskeg.
- The Fort Clatsop unit contains a small sphagnum swamp. John Christy, plant ecologist with the Oregon Natural Heritage Program, reported in 2000 that this site located in the headwaters of Salamander Creek was the only known stand of its type in Oregon. No other spruce-swamps in Oregon contain sphagnum. Sphagnum becomes more common farther north in Washington and British Columbia.

Paleontology (from Fay et al. 2009)

- Fossils may be found in almost all of the rock units that underlie or surround LEWI.
- Foraminifera in Crescent Formation in area of Fort Columbia State Park.
- Landslides at Ecola State Park have exposed portions of the Astoria Formation with fossil foraminifera.
- No paleontological specimens curated by LEWI.
- Invertebrates, shark, fish, and trace fossils have been found outside park boundaries.
- Cultural context: archeological specimens may contain paleontological significance; bivalves from shell middens near Seaside indicated that a quieter-water, bay-type environment prevailed during the last 3,500 years.

Disturbed Lands

- Active wetland restoration is ongoing.
- Logging roads are being decommissioned.

Mineral Exploration and Development

- Fort Clatsop contains an historic clay pit.

Type Sections

- None on park lands.
- The Astoria Formation's type section is in Astoria, Oregon, but is inaccessible as a result of urban development.

Marine

- No marine features; park does not extend offshore.

Field Trip (Tom Horning and Ian Madin)

On Thursday, October 15, participants met at Fort Clatsop for a field trip to the various park units. In the parking lot, Tom Horning discussed a core from Seaside, Oregon that he collected following the 1964 tsunami (fig. 4).

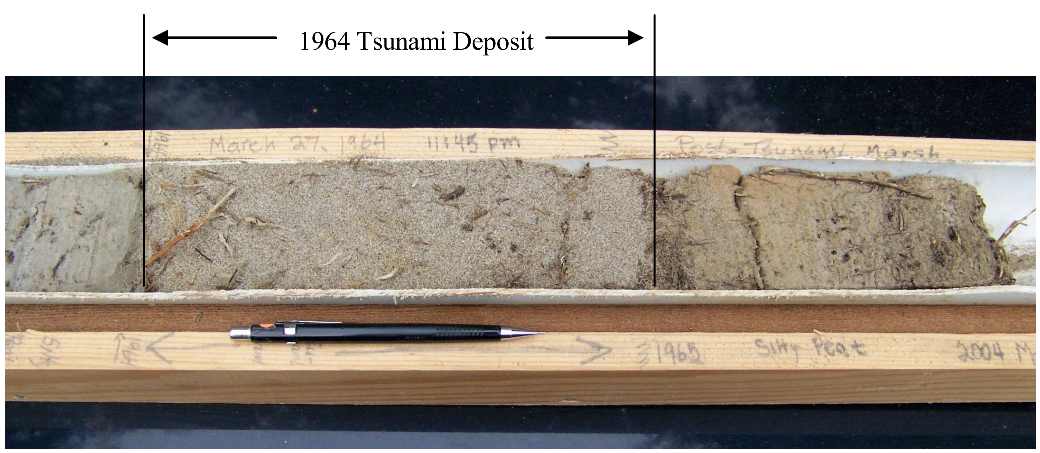

Figure 4. Core through sandy sediments deposited by the 1964 tsunami in Seaside, Oregon, courtesy of Tom Horning (Horning Geosciences). Silty peat overlies the tsunami deposit, which sharply overlies gray, silty clay. The top of the core is to the right. The pencil is 14 cm (5.5 in) long.

Stop 1: Cape Disappointment

- Sand accumulation behind North Jetty.
- Shoreline retreat because ebb-tide delta that once supplied sand is now eroding.
- Shoreline erosion and retreat peaked in 1998-99 because of the confluence of storms, high tides, and storm surges four times in one winter. Storms were focused into the Pacific Northwest by La Niña weather following the previous year's El Niño (Tom Horning, written communication, January 4, 2010).
- Without jetty, parking area and campground would be under water.
- McKenzie Rock was once a sea stack.
- Crescent Formation: early Eocene; forms bedrock; pillow basalts; shear fractures through rock; erosion of shear fractures develops sea caves.
- Columbia River dammed so sand supply would decrease even without the jetty; 6 million cubic yards/yr of sediment came down Columbia River.
- Mouth of Columbia River is dredged to keep open.
- Logs (driftwood) deposited in a crevice between two outcrops of Crescent Formation have replaced brush and shrubs that once grew there; sea has moved shoreline eastward.
- Magnetite-rick beach sand; black sand; very fine grained; well sorted; random grab sample contained easily over 50% magnetite grains under hand lens.
- Sea cave in Crescent Formation; once battered by waves, now surrounded by land; associated with shear fractures (several such caves occur at the base of sea cliffs in this area).

Stop 2: North Jetty at the mouth of the Columbia River

- Transgressive system: ultimately, beach retreating landward.
- Beach north of jetty: grows in summer; retreats in winter.
- Fencing installed to stabilize sand.
- Every winter, sand blows inland and covers vegetation and driftwood.
- Pillow basalt along bluffs is Crescent Formation; lighthouse anchored to basalt.

Drive to Fort Columbia State Park

- Pleistocene terraces, including elevated beach and dune sand representing an older, eroded spit.

Stop 3: Fort Columbia State Park

- Thrust faults in Crescent Formation.
- Eocene to Miocene uplift.
- High tide prohibited viewing other structures (basalt lapilli tuff near east end of tunnel on intertidal bench contains plagioclase crystals up to 12 cm [4.7 in] long).
- Bedrock shore; abundant driftwood in sheltered cove – tree trunks about 0.6 m (2 ft) diameter, log with 8 tractor tires (old dock).

Stop 4: Dismal Nitch

- Appropriately, viewed in the rain.
- Basaltic sandstone on flank of Crescent Formation; calcareous and zeolite cement; no particular bedding.
- Headland sheltered Corps of Discovery.

Stop 5: Short walk on undeveloped road north of Dismal Nitch

- Man-made cave dug into the steep creek bank; perhaps from mining days?.

Drive to Astoria Column

- Evidence of landsliding in Astoria neighborhoods: offset sidewalks; cracks in retaining walls; buckling streets; slumps and houses built on slumps.

Stop 6: Astoria Column panoramic overview

- Astoria Column constructed on Astoria Hill basalt ridgeline (about only place that isn't a landslide deposit).
- Baked contact between basalt and mudstone.
- Examples of invasive lava: Astoria Hill, Saddle Mountain and Tillamook Head to the south.
- Columbia Fault runs through Camp Rilea and Columbia River; two other faults; part of wrench tectonic couplet in NW Oregon.
- Coast Range rotating clockwise and movement distributed along faults.
- Cascades spreading apart – central graben in range.
- Subduction continues, but whole Coast Range is heading to Aleutian Islands; abundant offset and both right- and left-lateral strike-slip faults.
- Columbia River separates Washington, which is under compression, from Oregon, which is undergoing extension.
- Bend in the Columbia River at Portland is because the river is deflected by the Portland Hills uplift along reverse faults of the Portland Hills-Clatskanie Fault Zone.
- Inverted topography to the south from Nicolai Mountain lava delta (near Knappa) southwesterly through Saddle Mountain to Neahkahnie Mountain; area was once seafloor.
- Tillamook Head is a sill about 460 m (1,500 ft) thick that formed by invasion of lavas through the wall of a submarine canyon into the marine sequence.
- Panoramic view of Youngs and Lewis and Clark Rivers.

Drive south on Highway 101

- Pleistocene terraces.
- South of Skipanon River: road rises onto dune ridge.
- Dunes began forming approximately 4,000 years ago; series of younger dunes from the highway to the ocean.
- North-to-south trending linear ridges on golf course.

Stop 7: Sunset Beach

- Introduced beach grass has stabilized dunes; sand used to sweep 460 m (1,500 ft) inland but typically blows inland from 46 to 180 m (150 to 600 ft) today.
- Wet, stormy cycle: beach may drop 1 m (3 ft) in elevation, but dropped as much as 4 m (12 ft) during the 1999 La Niña winter.
- Before 1973, driftwood littered the beach, but the local population collected driftwood to heat their homes during the 1973 oil embargo; little driftwood remains on the beach today.
- Neacoxie Creek marks the old shoreline of 2,000 years before present.

Stop 8: Gearhart Fen

- Some confusion between a fen and a bog: EPA (http://www.epa.gov/owow/wetlands/types/fen.html) defines a fen as a peat-forming wetland that receives nutrients from sources other than precipitation; fens are less acidic than bogs and have higher nutrient levels; bogs receive water from precipitation rather than from runoff, groundwater, or streams and are characterized by spongy peat deposits, acidic waters, and sphagnum moss.
- A hydrologic study in 1995 determined groundwater flowed through the area, making the site a fen rather than a bog as had originally been believed.
- Nature Conservancy personnel claim that their Gearhart Fen preserve protects the southernmost occurrence of muskeg on the coast. As Christy stated in his 2000 report, sphagnum in the Fort Clatsop unit's spruce-swamp site does not occur elsewhere in Oregon.
- Peri-glacial environment about 22,000 years ago.
- Stunted growth to vegetation.
- Astoria Formation and possibly some Smuggler Cove Formation exposed east of fen.

Stop 9: Necanicum River Estuary

- Handout *A Geological and Botanical Tour of Neawanna Point Marsh, Necanicum River Estuary, Seaside* by Nancy Eid and Tom Horning (2009) illustrates where past beachfronts were located in relation to today's terraces and the influence of the 1964 tsunami.
- Missing gravel berm: The 1700 A.D. tsunami, which may have been 9 m (30 ft) deep, destroyed the berm, which was swept eastward, upstream, and transformed from a ridge to a planar sheet of rock. The 1964 tsunami covered the marsh surface with 2.4 m (8 ft) of water.
- Although salt water from the tsunami may have killed some of the trees, subsidence probably killed the pre-tsunami forest.
- Whole region warps upward due to subduction then elastically rebounds (subsides) when earthquakes occur.
- Beach berms form about 6 m (20 ft) above sea level; cobbles in the area were rolled into area during the tsunami, otherwise they would be closer to the shoreline.

Stop 10: Tsunami Coulee (3rd street, Seaside, Oregon)

- Surge channel during tsunami.
- Seaside, OR built westward on cobbles that avoided erosion.
- Able to swim in coulee 80 years ago but now, the coulee is filled with sand and mud.
- 3 tsunami sand layers found interbedded with silty peat beyond the east end of the tsunami coulee.
- Northeast flow direction to sand deposits suggest that Tillamook Head may have diverted tsunami waves to the north; diverted waves may have been superimposed on other waves to form mountains of water rather than a plateau of water.

Stop 11: Tsunami Island

- Boomerang shaped.
- Stratigraphy (from bottom to top): peat/cobbles/peat/sand with a sand layer sometimes interbedded with the peats and sometimes with the cobbles.
- Tsunami waves came through to the northeast and eroded out moat. The boomerang shape of the tsunami moat may have formed when downed trees that were swept eastward by the tsunami lodged against a stand of unusually strong spruces growing along the riverbank. The barrier of

horizontal trees lodged against the bigger standing trees may have allowed water to flow around the logjam, accelerate, and dig out the moat (Tom Horning, written communication, January 4, 2010).
- Could also be a constructional feature from when Seaside was first formed.
- Waves around Tillamook Head pushed cobble berm into this area.
- Gravels from landslides.
- Necanicum and Neacoxie Rivers were once the same river: a tsunami about 1,100 years ago flooded the area, drained north out of the city, breached cobble deposits, and formed 2 rivers.
- Rivers do not have enough energy to move the cobbles.

Stop 12: Quarry south of Seaside, OR
- Grande Ronde basalt sill intruded into blond-colored mudstone; mudstone is usually gray but baked to a yellow color by the dike.
- Sill is about 300 m (1,000 ft) thick.

Stop 13: Ecola State Park parking lot
- Landslides: recent scarps in hillsides adjacent to beach; lack of trees on older slumps.
- Lewis and Clark write about landslides here.
- Head scarp forms eastern border of park.
- Features: headlands, tombolos, sea stacks, Astoria Formation contorted around basalt, sea caves (undercut cliff), and landslides (mass wasting).

Stop 14: Ecola State Park, Indian Beach Parking Lot
- Location of the movie, *Goonies.*
- At beach, cross-section exposed of a tree stump overlain by gravels.
- Discussion of old growth forests.
- 80,000-year-old deposit, not 300-year-old deposit.
- Pleistocene wet period high stand; 300 years ago the bluff was located offshore because sea level was lower.

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Table 2. Scoping Meeting Participants

Name	Affiliation	Position	Phone	E-Mail
Bolitho, Zack	LEWI	Chief, Resource Management	503-861-4441	Zachary_bolitho@nps.gov
Cole, Carla	LEWI	Natural Resources Project Manager	503-861-4443	carla_cole@nps.gov
Davis, Marsha	NPS PWRO	Geologist	206-220-4262	Marsha_davis@nps.gov
Eid, Nancy	LEWI	Biologist	503-861-4445	nancy_eid@nps.gov
Graham, John	Colorado State U.	Geologist, GRI Report Writer	970-225-6333	rockdoc250@comcast.net
Heise, Bruce	NPS GRD	Geologist, GRI Program Coordinator	303-969-2017	bruce_heise@nps.gov
Horning, Tom	Horning Geosciences	Geologist	503-738-3738	horning@pacifier.com
Mack, Gregory	NPS PWRO	Geologist, GIS Specialist	206-220-4249	gregory_mack@nps.gov
Madin, Ian	DOGAMI	Chief Scientist	971-673-1542	Ian_madin@dogami.state.or.us
Stokeld, Rachel	LEWI	Museum Technician	503-861-4448	rachel_stokeld@nps.gov
Wood, Deborah	LEWI	Cultural Resource Program Manager	503-861-4448	deborah_s_wood@nps.gov