STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
DONALD A. HULL, STATE GEOLOGIST

Liquefaction Susceptibility Map of the Siletz Bay Area, Coastal Lincoln County, Oregon

1995

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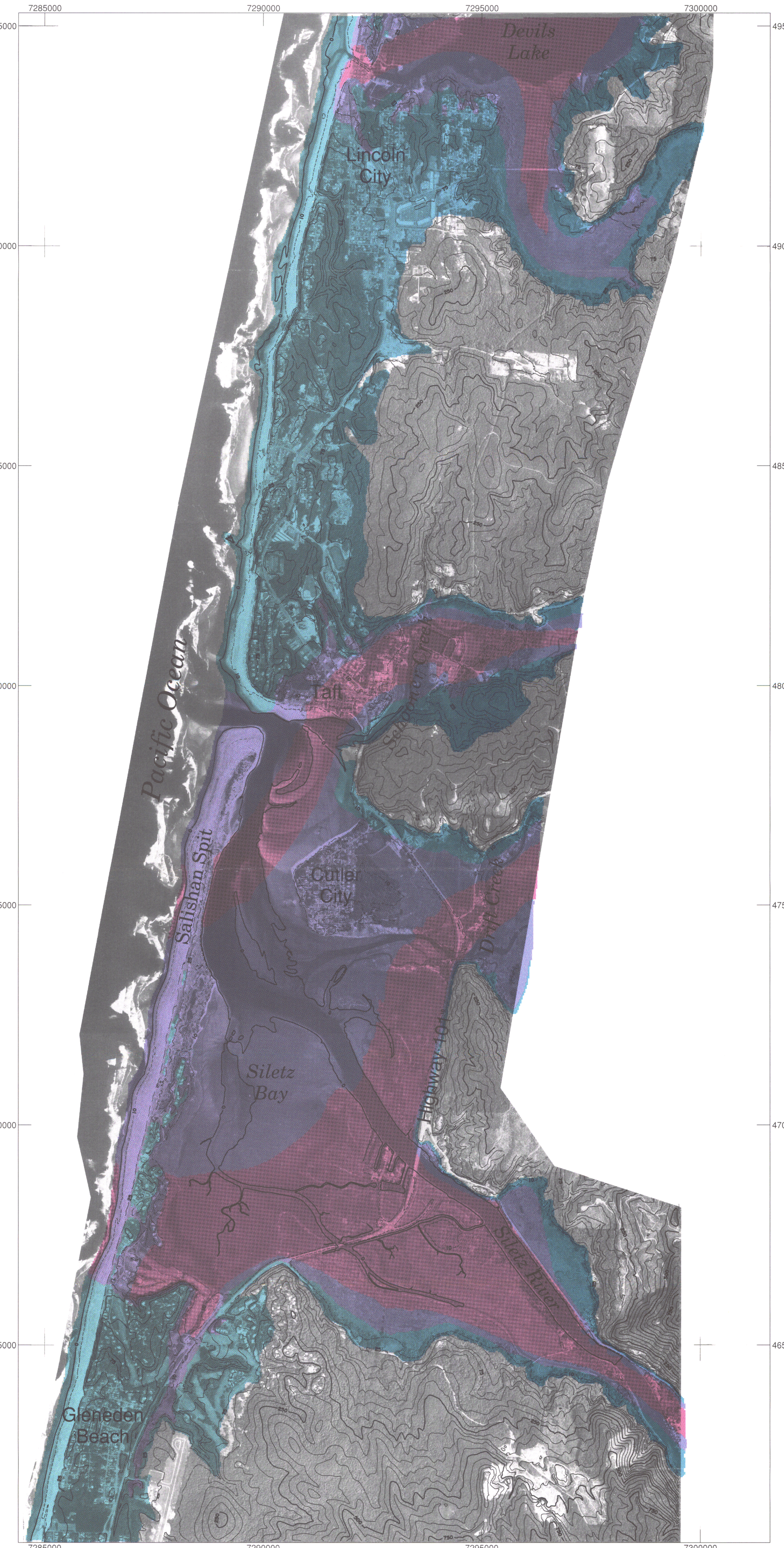
GMS-93

Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon

By Y. Wang and G. Priest

Map 1

Funds for this project were provided in part from the Oregon Coastal Management Program, Oregon Department of Land Conservation and Development, from funds provided by the Oregon Legislature, U.S. Department of Commerce National Oceanic and Atmospheric Administration Office of Ocean and Coastal Resource Management under Section 306 Coastal Zone Management grants, and Section 309 Program Enhancement grants, and State Lottery funds appropriated to the Oregon Department of Geology and Mineral Industries.



SCALE 1:24 000

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Projection and 5,000-foot grid ticks: Oregon coordinate system, north zone (Lambert conformal conic).

Horizontal datum: 1983 North American Datum.
Vertical datum: National Geodetic Vertical Datum of 1929.

PROJECT LOCATION

Analysis by Yumei Wang, Oregon Department of Geology and Mineral Industries and William J. Leonard

Cartography by Mark E. Neuhaus

This Liquefaction Susceptibility Map depicts four susceptibility zones (zones 0 to 3) for earthquake- induced liquefaction. Please read the companion text, which explains the liquefaction hazards associated with this map. Liquefaction susceptibility is defined in relative terms. Areas in the highest susceptibility zone have the greatest liquefaction hazard and are likely to suffer the most intense damage from liquefaction; those in the lowest hazard zone are likely to suffer the least.

Liquefaction, the loss of soil strength due to increases in pore pressures, is often compared to "quicksand". Loose, water saturated, sandy soils can liquefy from earthquake shaking and can produce extensive damage. Hazards often involve structural and foundation failures due to differential movement in the vertical direction between the structure and the ground, and lateral spreading, that is, horizontal movement of surface soil layers down gentle slopes or towards free faces (such as river banks). Ruptured pipelines, displaced bridge abutments, damaged buildings and other structures, and flotation of buoyant underground structures are potential hazards associated with liquefaction.

This Liquefaction Susceptibility Map may be used to gain an understanding of liquefaction hazards, so steps may be taken to reduce the risk to life and property through planning policy and other mitigation measures. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens. This map was developed as a regional planning tool and does not have site specific accuracy. All areas shown on the map are susceptible to severe earthquake shaking regardless of the assigned zone.

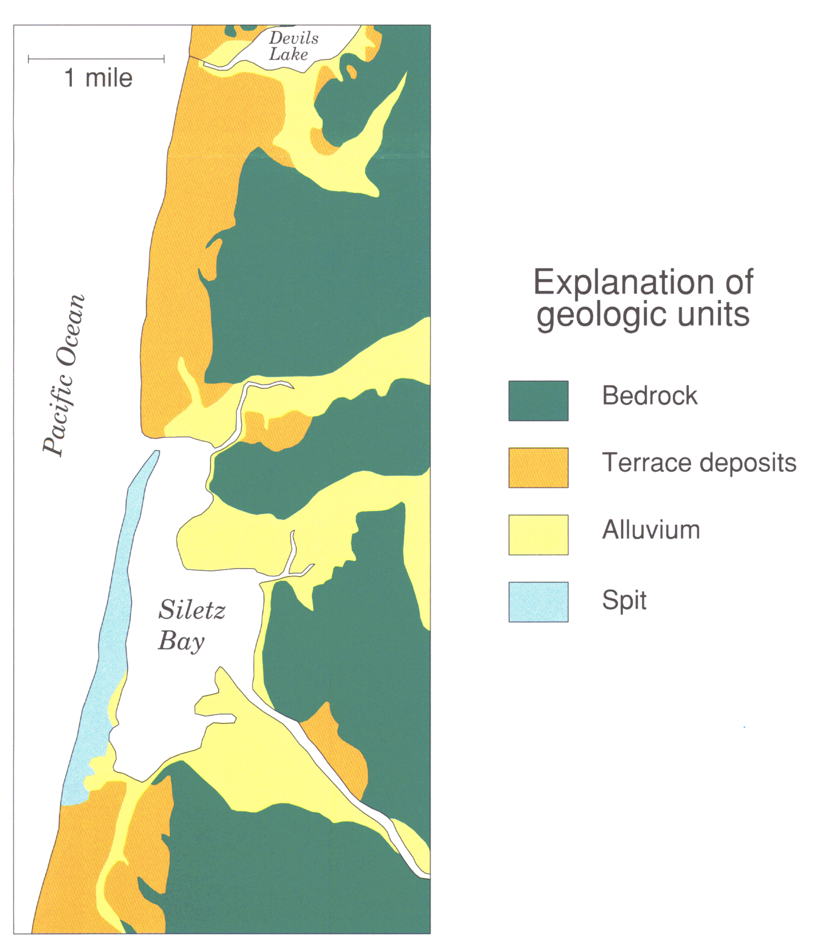
Liquefaction susceptibility

Zone 3
Highest. Extensive lateral spreading and flow failures possible.

Zone 1
Lowest. Localized liquefaction possible.

Zone 2
Intermediate.

Zone 0
No. Possible exception in small localized areas.



Disclaimer

Information provided in this publication should NOT be used in place of site-specific studies. The relative hazard zones are not intended to replace site-specific evaluations, such as for engineering analysis and design. Site-specific earthquake hazards should be assessed through geotechnical investigation by qualified practitioners.

STATE OF OREGON
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Amplification Susceptibility Map of the Siletz Bay Area, Coastal Lincoln County, Oregon

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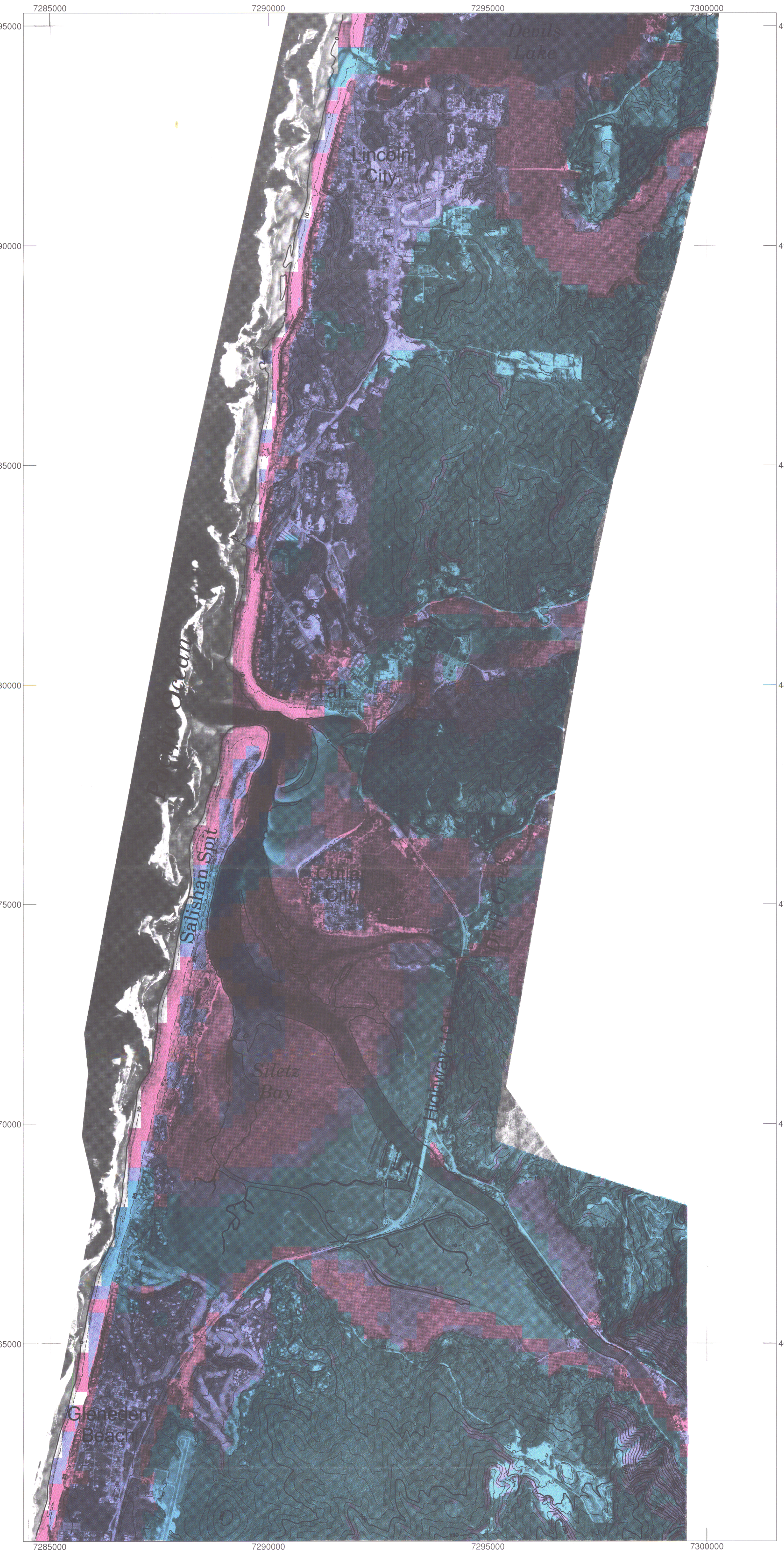
Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon

By Y. Wang and G. Priest

Map 2

Funds for this project were provided in part from the Oregon Coastal Management Program, Oregon Department of Land Conservation and Development, from funds provided by the Oregon Legislature, U.S. Department of Commerce National Oceanic and Atmospheric Administration Office of Ocean and Coastal Resource Management under Section 306 Coastal Zone Management grants, and Section 309 Program Enhancement grants, and State Lottery funds appropriated to the Oregon Department of Geology and Mineral Industries.



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Horizontal datum: 1983 North American Datum.
Vertical datum: National Geodetic Vertical Datum of 1929.

PROJECT LOCATION

Analysis by Yumei Wang, Oregon Department of Geology and Mineral Industries

Cartography by Mark E. Neuhaus

This Amplification Susceptibility Map depicts three susceptibility zones (zones 1 to 3) for amplification of peak ground accelerations (PGA) associated with earthquake shaking. Amplification at a range of frequencies is not depicted. Please read the companion text, which explains the amplification hazards associated with this map. PGA amplification susceptibility is defined in relative terms. Areas in the highest susceptibility zone have the greatest PGA amplification hazard from a significant earthquake; those in the lowest hazard zone have the lowest PGA amplification hazard.

Strong ground motions can cause severe damage to the built environment, such as to buildings and lifelines. Ground shaking amplification generally occurs in unconsolidated, younger soils (alluvium, spit, and terrace deposits) as opposed to harder, older bedrock (see geology map). Amplification can greatly increase the danger of building damage and non-structural damage, such as broken windows, fallen ducts, or overturned bookcases. Thick deposits of soft soils often experience significant amplification at an intermediate frequency range not shown on this map and prolonged shaking, which may lead to extensive damage.

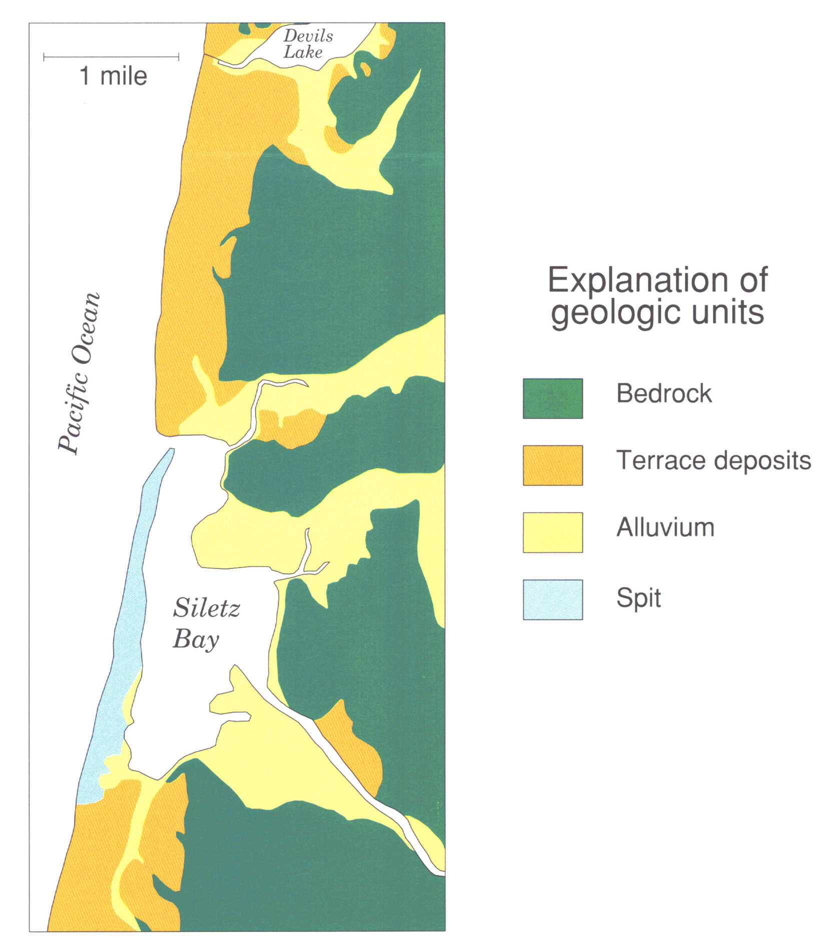
This Amplification Susceptibility Map may be used to gain an understanding of the ground shaking amplification hazards in the higher frequency (or shorter period) response domain, and is especially useful for structures with shorter periods. The frequencies of ground shaking that lead to damage to buildings are a function of a building's height, shape, and construction type. Steps may be taken to reduce the risk to life and property through planning policy and other mitigation measures. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens. This map was developed as a regional planning tool and does not have site specific accuracy. All areas shown on the map are susceptible to severe earthquake shaking regardless of the assigned zone.

Amplification susceptibility

Zone 3
Highest.

Zone 2
Intermediate.

Zone 1
Lowest. Localized amplification possible.



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STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
DONALD A. HULL, STATE GEOLOGIST

Landslide Susceptibility Map of the Siletz Bay Area, Coastal Lincoln County, Oregon

1995

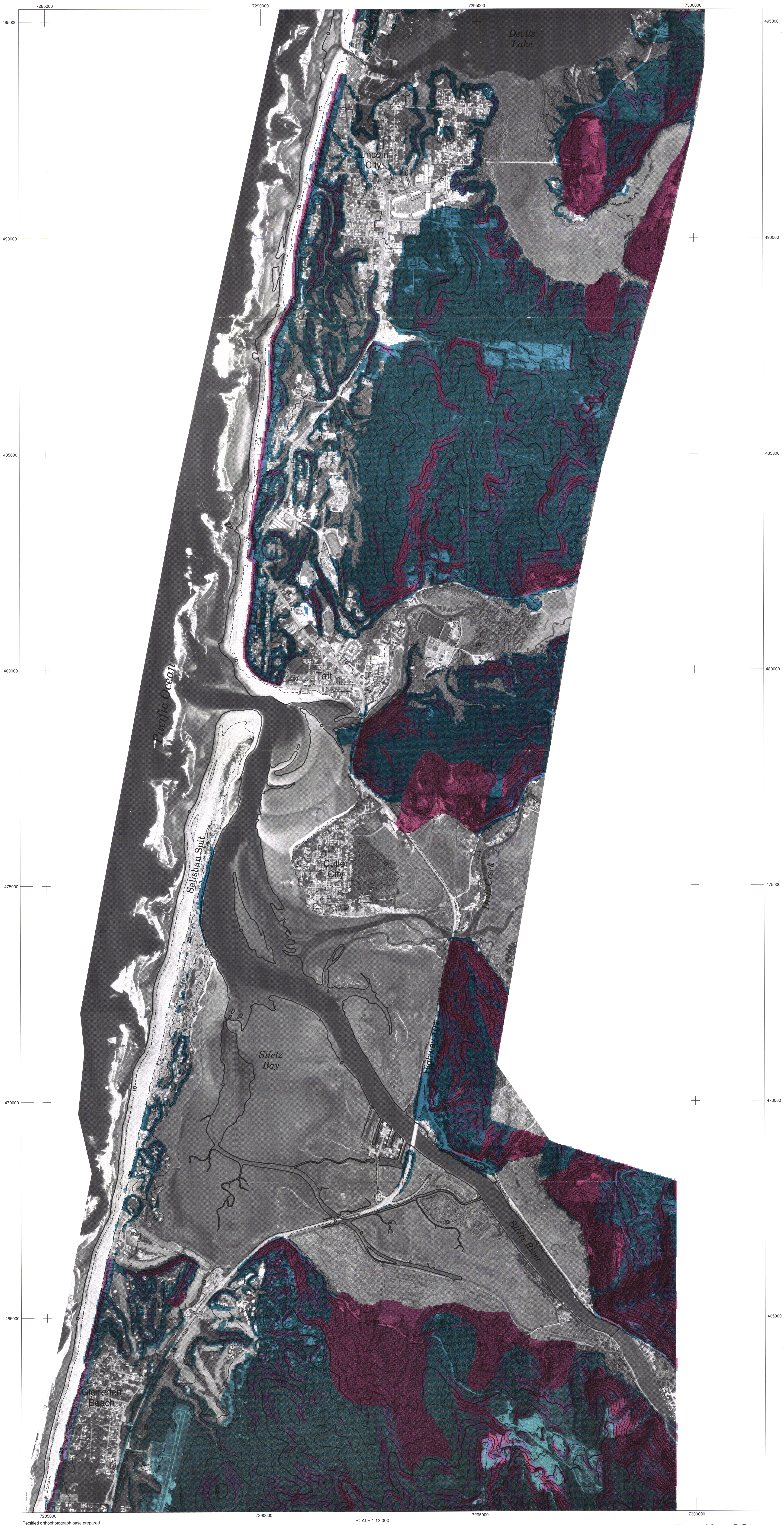
GMS-93

Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon

By Y. Wang and G. Priest

Map 3

Funds for this project were provided in part from the Oregon Coastal Management Program, Oregon Department of Land Conservation and Development, from funds provided by the Oregon Legislature, U.S. Department of Commerce National Oceanic and Atmospheric Administration Office of Ocean and Coastal Resource Management under Section 306 Coastal Zone Management grants, and Section 309 Program Enhancement grants, and State Lottery funds appropriated to the Oregon Department of Geology and Mineral Industries.



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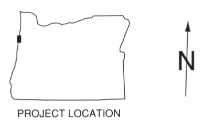


PROJECT LOCATION

SCALE 1:12 000

.5 0 1 2 KILOMETERS

1000 0 7000 FEET

.5 0 1 MILES

Analysis by Yumei Wang and George R. Priest, Oregon Department of Geology and Mineral Industries

Cartography by Mark E. Neuhaus

This Landslide Susceptibility Map depicts four susceptibility zones (zones 0 to 3) for landsliding associated with earthquake shaking. Please read the companion text, which explains the landsliding hazards associated with this map. The landslide susceptibility is defined in relative terms. Areas in the highest susceptibility zone have the greatest landsliding hazard and are likely to suffer the most intense damage related to landslides; those in the lowest hazard zone are likely to suffer the least.

Landslides, which generally occur on steep slopes composed of weak rock or soil, can be triggered by earthquake motions. Earthquakes can reactivate landslide areas or generate new slide movements. Landslide activities can bury extensive areas, damage structures, and destroy or block roads. Areas affected by human activities, such as roadcuts and mine excavations, have not been specifically addressed. If the necessary conditions are present, landslides may occur without the influence of earthquakes. These conditions include unusually heavy or prolonged rainfall and oversteepening of slopes by natural processes or human influence.

This Landslide Susceptibility Map may be used to gain an understanding of landslide hazards, so steps may be taken to reduce the risk to life and property through planning policy and other mitigation measures. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens. This map was developed as a regional planning tool and does not have site specific accuracy. All areas shown on the map are susceptible to severe earthquake shaking regardless of the assigned zone.

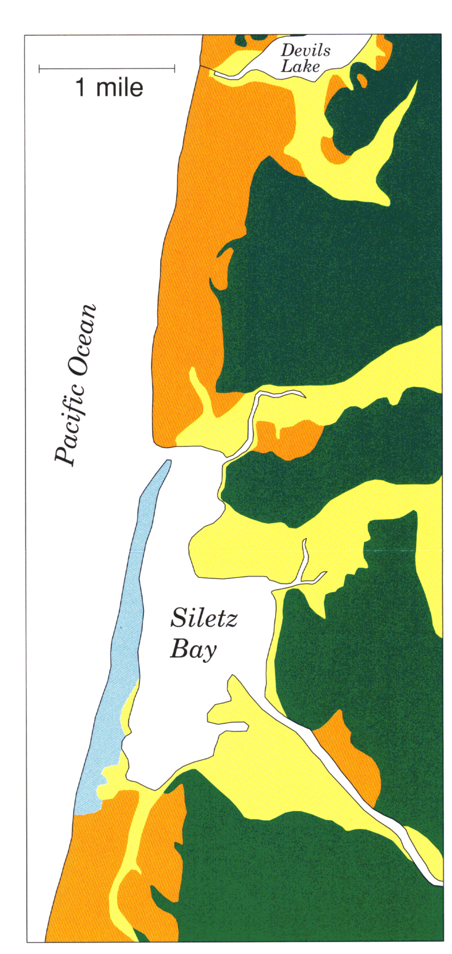
Landsliding susceptibility

Zone 3
Highest. May be extensive.

Zone 2
Intermediate.

Zone 1
Lowest. Localized landsliding possible.

Zone 0
No. Possible exception in small localized areas.



Explanation of geologic units

Bedrock
Terrace deposits
Alluvium
Spit

Disclaimer

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Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon

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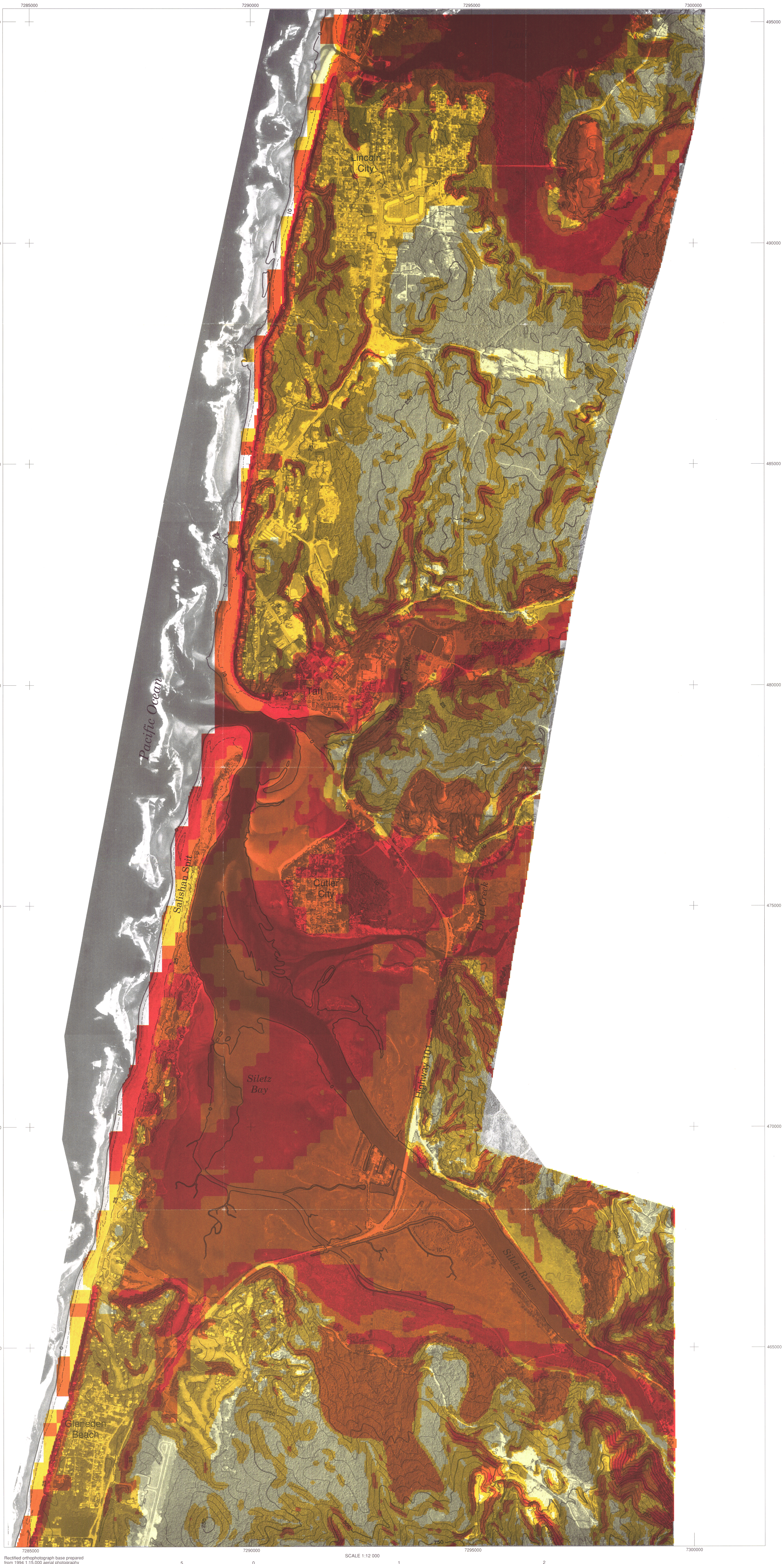
Map 4

Funds for this project were provided in part from the Oregon Coastal Management Program, Oregon Department of Land Conservation and Development, from funds provided by the Oregon Legislature, U.S. Department of Commerce National Oceanic and Atmospheric Administration Office of Ocean and Coastal Resource Management under Section 306 Coastal Zone Management grants, and Section 309 Program Enhancement grants, and State Lottery funds appropriated to the Oregon Department of Geology and Mineral Industries.



This Relative Earthquake Hazard Map depicts four zones (zones A to D) of relative earthquake hazards. Please read the companion text, which explains the earthquake hazards associated with this map. The susceptibility to earthquake hazards are defined in relative terms. Areas in the highest susceptibility zone are likely to suffer the most intense damage related to ground response; those in the lowest hazard zone are likely to suffer the least.

Three earthquake hazards that are associated with local geology (liquefaction, amplification, and landsliding) were individually evaluated and then combined to develop the Relative Earthquake Hazard Map. Individual hazard assessments are shown on the companion plates (maps 1 through 3).

This composite map allows technical and nontechnical users to gain an understanding of earthquake hazards, so steps may be taken to reduce the risk to life and property through planning policy and other mitigation measures. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens.

The map series was developed as a regional planning tool and does not have site-specific accuracy. All areas shown on the map are susceptible to severe earthquake shaking regardless of the assigned zone.

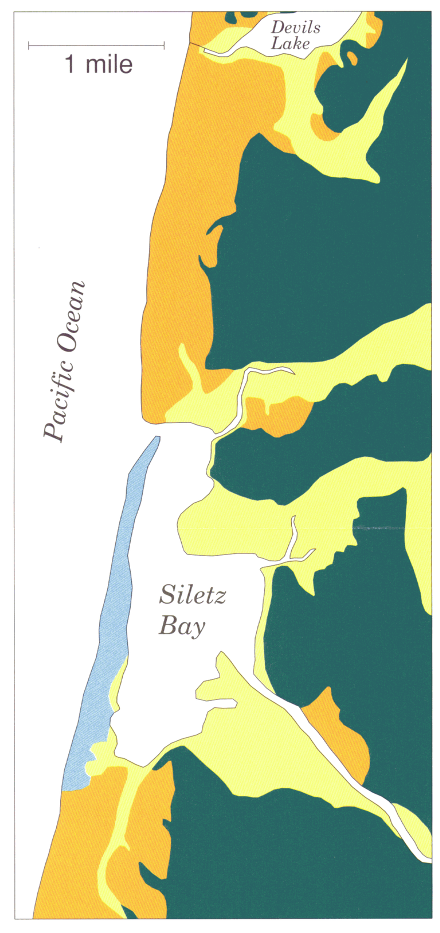
Hazard susceptibility

Zone A
Highest. Intense ground response and failures possible

Zone B
Intermediate to highest

Zone C
Lowest to intermediate.

Zone D
Lowest.



Explanation of geologic units

- Bedrock
- Terrace deposits
- Alluvium
- Spit

Rectified orthophotograph base prepared from 1994 1:15,000 aerial photography taken by Spencer B. Gross, Inc.

Projection and 5,000-foot grid ticks: Oregon coordinate system, north zone (Lambert conformal conic).

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PROJECT LOCATION

N

SCALE 1:12 000

.5 0 1 2 KILOMETERS

1000 0 7000 FEET

.5 0 1 MILES

Analysis by Yumei Wang, Oregon Department of Geology and Mineral Industries

Cartography by Mark E. Neuhaus

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STATE OF OREGON
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Geological Map Series
GMS–93

Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon

By
Yumei Wang and George R. Priest
Oregon Department of Geology and Mineral Industries

1995

Funded in part by
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Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon

By Yumei Wang and George R. Priest, Oregon Department of Geology and Mineral Industries

ABSTRACT

This Relative Earthquake Hazard Map series was developed to identify and characterize earthquake hazards in the greater Siletz Bay area of coastal Lincoln County, Oregon. The publication includes text and the following maps: (1) *Liquefaction Susceptibility Map*, (2) *Amplification Susceptibility Map*, (3) *Landslide Susceptibility Map*, and (4) *Relative Earthquake Hazard Map*. These maps show zones of relative susceptibility to earthquake-induced liquefaction, amplification of peak ground acceleration, landslides, and general earthquake hazards, respectively. Areas within the highest susceptibility zone have the greatest hazard and are likely to suffer the most intense damage related to ground response; those in the lowest hazard zone are likely to suffer the least.

Three earthquake hazards related to site geology (liquefaction, amplification, and landsliding) were individually evaluated and then combined to develop the *Relative Earthquake Hazard Map* (Map 4). This hazard map allows both technical and nontechnical users to gain an understanding of earthquake hazards and take steps to reduce the risk to life and property through planning policy and other mitigation measures. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens.

The map series was developed as a regional planning tool and does not have site-specific accuracy. All areas shown on the map are susceptible to severe earthquake shaking due to the regional earthquake setting.

FOREWORD

The techniques used to prepare portions of these maps were developed for the hazard maps of the Portland, Oregon, metropolitan area. The two initial publications from that study area are suggested as supplemental reading (Mabey and Madin, 1993; Mabey and others, 1993).

A tsunami hazard map using the orthophoto base map used for this report will be published by the Oregon Department of Geology and Mineral Industries in the near future (Priest and others, in preparation).

The list of selected references at the end of this report is divided into four sections: general information and liquefaction, amplification, and landslides—the three earthquake hazard types that were analyzed and are discussed separately below. References in the text refer to the corresponding section of the list.

INTRODUCTION

This report was developed to identify and characterize earthquake hazards in the greater Siletz Bay area of coastal Lincoln County, Oregon (Figure 1). The study area, which is located in a region of potential seismic activity, lies just east of the Cascadia deformation front, where large-magnitude subduction zone earthquakes are thought to have occurred in the past few thousand years. This study does not predict the size, location, or frequency of damaging earthquakes. Instead, it evaluates the ground response influenced by site geology due to ground motions imparted by a major earthquake.

The report includes the following maps: (1) *Liquefaction Susceptibility Map*, (2) *Amplification Susceptibility Map*, (3) *Landslide Susceptibility Map*, and (4) *Relative Earthquake Hazard Map* (Maps 1 to 4). The hazards are defined in relative terms: Areas within the highest susceptibility zone have the greatest hazard in a significant earthquake and are likely to suffer the most intense damage related to ground response. Those in the lowest susceptibility zone are likely to suffer the least.

Three earthquake hazards (liquefaction, amplification of peak

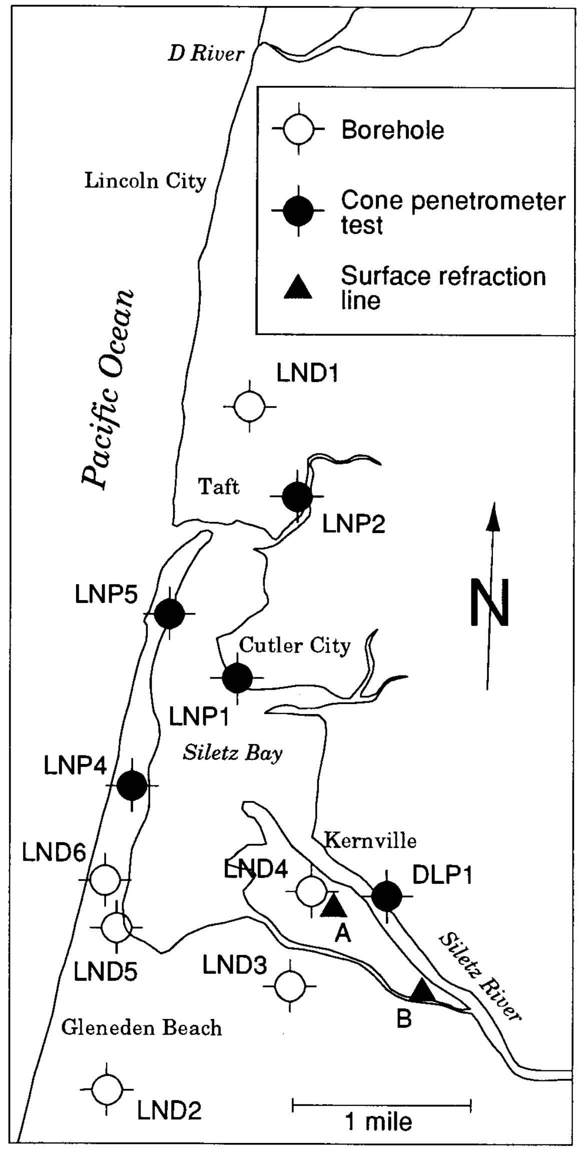

Figure 1. Map showing study area and exploration locations.

ground acceleration, and landsliding) were individually evaluated and are shown separately on the companion maps (Maps 1 to 3). The *Relative Earthquake Hazard Map* (Map 4) was developed by combining the individual hazard maps. The *Relative Earthquake Hazard Map* is designed to allow both technical and nontechnical users to gain an understanding of the regional earthquake hazard. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens.

The goal of this study is to encourage and facilitate cost-effective mitigation actions to reduce loss of life, injury, and property damage in future earthquakes. Policy makers seeking to implement such actions can use these maps as aids in planning and setting priorities.

Due to the regional earthquake setting, all locations that are within the mapped area are susceptible to strong ground shaking and other earthquake hazards, regardless of the assigned zone. For example, a great subduction zone earthquake would affect a large coastal area, and all areas shown on the maps could experience strong earthquake shaking. The maps do **NOT** have site-specific accuracy.

DISCLAIMER

The results and conclusions of this report are necessarily based on limited data, resources, and available time spent on the project and include subjective assumptions. Information provided in this publication should **NOT** be used in place of site-specific studies. The relative hazard zones are not intended to replace site-specific evaluations, such as for engineering analysis and design. Site-specific earthquake hazards should be assessed through geotechnical investigation by qualified practitioners.

EARTHQUAKE HAZARDS

During the late 1980s, the threat of a Cascadia Subduction Zone earthquake in the Pacific Northwest became widely accepted. Scientists believe that all parts of Oregon, including the Siletz Bay region, can be shaken by earthquakes. These earthquakes can occur in the Juan de Fuca plate (intraplate earthquakes), in the overriding North American plate (crustal earthquakes), or along the interface between the two plates (subduction zone earthquakes). Coastal areas have an additional hazard from tsunamis, sometimes (incorrectly) referred to as tidal waves.

All three possible earthquake types (subduction, intraplate, and crustal) can severely impact the region and were analyzed as part of this study. The epicentral distances and horizontal ground accelerations used in the analyses are presented in Table 1. The earthquake magnitudes modeled for subduction, intraplate, and crustal earthquakes were M8.1 to M8.5, M7.3, and M6 to M6.6, respectively.

EARTHQUAKE EFFECTS

The most severe damage from an earthquake is usually concentrated near the rupture zone and in areas where site geology enhances damage. Poor ground conditions that commonly contribute to damage are associated with the following phenomena:

Liquefaction, where saturated, loose, sandy soils become unstable like "quicksand."

Amplification, where ground shaking is intensified, especially in "soft" soils.

Landsliding, where "weak" slopes destabilize and move downhill.

These phenomena, which are discussed in the following subsections, have been evaluated in a **relative sense**. That is, the maps do **not** depict the **absolute** degree of earthquake hazard at any site. For any given earthquake, it is possible to incur minimal damage even in the highest susceptibility zone or extensive damage even in the lowest susceptibility zone.

MAP-MAKING METHODOLOGY

The hazard maps are based on the local geology, engineering properties of the geologic units, state-of-practice geotechnical engineering analysis, and professional judgment. The methodology includes developing a three-dimensional geologic model; measuring and estimating relevant geotechnical parameters for units in the geologic model; developing earthquake scenarios; selecting input parameters for the analyses of earthquake-induced liquefaction, ground motion amplification, and landsliding; performing the individual analyses; producing the individual hazard maps; and, lastly, producing the relative earthquake hazard map.

The three-dimensional geologic model for the study area was developed by obtaining (1) information on regional surface geology from published geologic maps, and (2) subsurface geologic data and information from the exploratory program performed for this study and from outside sources, including governmental agencies and consultants. Table 2 lists the results of the exploratory program conducted as part of this study, which consisted of boreholes, cone penetrometer tests, and geophysical surface refraction profiles. Exploration locations are shown on Figure 1. Existing data included water well logs, borehole logs, and interpreted cross sections from drilling and geophysical studies.

Data on engineering properties were obtained from existing sources and from new work performed for this study. Values were selected for geologic units based on in situ measurements, laboratory tests, and data provided in the technical literature. In situ measurements conducted as part of this study involved geophysical surface refraction profiles, downhole shear wave velocity tests, cone penetrometer tests including shear wave velocity measurements, and standard penetration tests.

The above data were integrated into a three-dimensional computer model of the geology on a 30-ft grid. Analytical methods

Table 1. *General earthquake parameters used in hazard analyses*

Earthquake	Magnitude	Horizontal distance to source zone in km	Peak horizontal acceleration values a_{max} in *g*[1]
Subduction zone event (interface)	8.1–8.5	19–65	0.15, 0.35, 0.55
Intraplate event (deep subduction zone)	7.3	40–50	0.15, 0.30, 0.45
Local crustal event (shallow)	6–6.6	0–25	0.15, 0.30, 0.45

[1] Values used in amplification analyses.

used to develop the maps are described in later subsections. Material property values assigned to specific geologic data layers are presented in Table 3. The data layers are presented on 1:12,000-scale and 1:24,000-scale rectified orthophoto base maps, which were produced as part of this study.

LOCAL GEOLOGIC SETTING

The study area, which extends from Dee River on the north to Gleneden Beach on the south, encompasses the Siletz Bay estuary (Figure 1). Siletz River is the major tributary of the bay; minor tributaries are Schooner Creek and Drift Creek. The local topography ranges from flat in the low-lying alluvial plains adjacent to drainages to moderate and steep in the mountainous bedrock areas bordering the river valleys. Annual precipitation is between 80 and 90 in., and flooding along the Siletz River is common.

Sedimentary and volcanic bedrock are locally overlain by younger deposits. Detailed descriptions of the geologic units can be found in Schlicker and others (1973) and Snavely and others (1976). The sedimentary rock units, consisting of sandstone, siltstone, and mudstone, include the Yamhill Formation (middle and upper Eocene), Nestucca Formation (upper Eocene), Alsea Formation (Oligocene), and Yaquina Formation (upper Oligocene and lower Miocene). The volcanic rocks include camptonite intrusive rocks (upper Eocene and lower Oligocene?) and Depoe Bay Basalt (middle Miocene).

Overlying the bedrock are younger deposits of sediment in-

Table 2. *Summary of exploratory program*

		SPC coordinates (ft)[1]			
		East	North	Depth (ft)	Units encountered[2]
Cone penetrometer test	LNP1	7291097	474580	27	Qal
	LNP2	7292848	480174	45	Qal
	LNP4	7288134	471357	42	Qal
	LNP5	7288950	476491	29	Qal
	DLP1	7295743	467694	131	Qal
Borehole	LND1	7291316	483200	71	Terrace, bedrock
	LND2	7287302	461630	100	Qaf, bedrock
	LND3	7291763	464930	142	Col, Qls, Qal, bedrock
	LND4	7293267	467749	210	Qaf, Qal, bedrock
	LND5	7287448	467050	150	Qaf, Qal, bedrock
	LND6	7287353	468341	50	Qal (dune), terrace
Geophysical surface refraction lines	A	7296379	464760	500	Qaf, Qal, bedrock
	B	7293267	467749	700	Qaf, Qal, bedrock

1 State Plane Coordinate System, north zone. Approximate locations for refraction lines A and B.
2 Qal = alluvium, Qaf = fill, Col = colluvium, Qls = landslide.

Table 3. *Material property values*

Geologic description	Shear wave velocity V_s (m/s)[1]	Unit weight (pcf)[2]
Alluvium	220	110
Tidal flat muds	130	90
Terrace sands between 0 and 50-ft depth	410	130
Dune sand	220	120
Bedrock (mostly marine sedimentary)	720	140

1 Weighted average shear wave velocity value from exploratory boreholes and cone penetrometer tests listed on Table 2; m/s = meters per second
2 pcf = pounds per cubic foot

cluding coastal marine terraces (Pleistocene), river terraces (Pleistocene and Holocene); alluvium (Holocene); and beach, bar, and dune sands (Holocene). Coastal marine terraces, which are composed mostly of weakly cemented sand, are flat-lying areas that extend up to 1 mi inland. Marine terrace deposits lie on a wave-cut bedrock platform that slopes gently seaward and form a nearly vertical cliff at the present shoreline. Perched deposits adjacent to bedrock slopes have been mapped as river terraces. Extensive alluvial deposits exist along rivers, streams, and estuaries. River terraces and alluvium are mostly silt, sand, and clay with some gravel. Beach, bar, and dune sand have been mapped along the shoreline and Siletz Spit. A simplified geologic sketch map included on companion maps illustrates surficial contacts between bedrock and younger deposits.

Both bedrock and younger deposits can be hazardous during an earthquake. For example, the younger alluvial deposits tend to be more susceptible to liquefaction and ground motion amplification than the older geologic deposits. In contrast, bedrock slopes composed of the Yamhill, Nestucca, and Alsea Formations are in many areas susceptible to landsliding (e.g., mapped landslides of Snavely and others, 1976). Identifying active faults is outside the scope of this study, and no active faults are shown on the hazard maps.

LIQUEFACTION SUSCEPTIBILITY ANALYSIS

General

Liquefaction is the process by which water-saturated, granular soils temporarily lose shear strength and behave as a viscous liquid rather than as a solid. When soils liquefy (often compared to "quicksand"), they temporarily take on "liquid" characteristics and may not provide adequate foundation support. Earthquake ground shaking can trigger liquefaction by increasing pore water pressures to levels where stable soil grain structure becomes unstable. The soils most susceptible to liquefaction are young, loose, clean sands and silts that are below the ground-water table.

Liquefaction-induced ground failure is a major cause of earthquake damage. Hazards often involve structural and foundation failures due to differential movement in the vertical direction between the structure and the ground and lateral spreading, that is, horizontal movement of surface soil layers down gentle slopes or toward free faces (such as river banks). Ruptured pipelines, displaced bridge abutments, damaged buildings and other structures, and flotation of buoyant underground structures are potential hazards associated with liquefaction.

The great 1964 Alaska earthquake, which was a moment magnitude 9.2 (M_w) subduction zone event, caused extensive damage related to liquefaction, sometimes affecting several tens of square miles (McCulloch and Bonilla, 1970; Combellick, 1993). Lateral spreading of flat to nearly flat ground was observed as far as 1,000 ft back from the edges of rivers and streams.

Methodology and discussion

The general procedures used to evaluate liquefaction susceptibility are to (1) gather subsurface data, (2) perform laboratory tests and analyze results, (3) analyze site-specific data to assess geologic-unit characteristics and ground-water levels with respect to liquefaction, (4) select and apply engineering parameters representative of geologic units based on site-specific analyses, and (5) categorize liquefaction susceptibility for map presentation.

The subsurface data were obtained through means described in the section "Map-Making Methodology." Standard-of-practice liquefaction analyses were performed on a limited database of 22 sites with techniques set forth by Seed and others (1983). Only the upper 50 ft of younger sediments were considered in the liquefaction analysis.

Conservative values were selected to map the liquefaction susceptibility. This approach, commonly used for regional mapping, was adopted to avoid underestimating hazards. The potentially liquefiable layers were characterized by slightly conservative engineering parameters, and a large earthquake (M8.5) with a horizontal ground acceleration of 0.35 *g* was selected to represent critical, yet plausible, conditions. This acceleration value is in general agreement with the 1993 Geomatrix numerical simulation values plotted on the attenuation relationship for a 20-km distance (Geomatrix Consultants, 1995). The conservatism, which tends to overestimate the liquefaction susceptibility in nearly all instances, accounts for most uncertainties. For local areas, a site-specific study would provide more precise data and may reduce the conservative estimates associated with this map.

The susceptibility for liquefaction was determined by (1) estimating the amount of liquefiable materials in the upper 50 ft, then (2) applying estimated ground-water levels to determine the available (i.e., loose and saturated) thickness of liquefiable material. The susceptibility zones were developed on the basis of available thickness of liquefiable material as follows: lowest for less than 10 ft of material; intermediate for 10 to 30 ft; and highest for greater than 30 ft.

The results from the analysis indicate that areas near former stream channels have the highest susceptibility for liquefaction. Generally, the low-lying areas within the drainages have an intermediate susceptibility, and outlying drainage areas and terraces are in the lowest susceptibility zone. Bedrock areas are not considered to be liquefiable.

Settlement, lateral spreading, flow failures, and other ground failures associated with liquefaction were not specifically evaluated. In addition, areas of loose, unsaturated soils that cannot liquefy can experience settlement.

Map presentation

The *Liquefaction Susceptibility Map* (Map 1) depicts four zones of relative susceptibility to liquefaction associated with earthquake shaking. Areas within the highest susceptibility zone (Zone 3) were analyzed to have the greatest liquefaction hazard and are anticipated to suffer the most intense liquefaction during a significant earthquake. The liquefaction susceptibility hazard zones are defined as follows:

Zone	Color	Liquefaction susceptibility
Zone 3	Pink	Highest. Extensive lateral spreading and flow failures possible.
Zone 2	Purple	Intermediate.
Zone 1	Green	Lowest. Relatively stable. Localized liquefaction possible.
Zone 0	White	None. Possible exception in small localized areas.

AMPLIFICATION SUSCEPTIBILITY ANALYSIS

General

Earthquake ground motions can be significantly modified by geologic deposits near the ground surface. This modification can intensify the ground shaking, which is termed ground motion (or ground shaking) amplification. Modifications can also decrease the ground motions or otherwise change characteristics (such as frequency or duration) of shaking. Map 2 shows amplification of peak ground acceleration (PGA), which can appropriately be applied to structures with higher frequency (shorter period) response, such as typical short buildings. Map 2 does not depict ground motion amplification at a range of frequencies. The frequencies of ground shaking that lead to damage to buildings are a function of a building's height, shape, and construction type.

Strong ground motions can produce severe damage to the built environment, such as buildings and lifeline systems. Amplification generally occurs in unconsolidated, younger soils as opposed to harder and older bedrock. It is largely influenced by soil thickness and engineering properties, such as shear wave velocity, which characterizes the stiffness of the soil. Ground-shaking hazards that are enhanced because of amplification involve both structural engineering failures and nonstructural damage (such as broken windows, fallen ducts, or overturned bookcases). Total building collapse is the most extreme structural engineering failure. Thick deposits of soft soils often experience significant amplification at an intermediate frequency range (not shown on Map 2) and prolonged shaking, which may lead to extensive damage.

The 1985 Mexico City earthquake, which was a surface-wave magnitude 8.1 (M_s) subduction zone event, caused dramatic building damage related to amplification (and more specifically, soil-structure interaction). The northwest portion of the city, which overlies clay-rich lake bed deposits, suffered very high shaking intensity and heavy damage. The predominant frequencies of ground shaking were coincident with the periods (or frequencies) of tall buildings and caused extensive building damage. More than 20 percent of the buildings greater than five stories high (totaling over 200) were seriously damaged (Seed and Sun, 1989), and over 10,000 people died.

Methodology and discussion

The two fundamental considerations for estimating ground shaking amplification are the input motion specification and the characterization of dynamic material properties. As described in the "Earthquake Hazards" section, there are three earthquake sources (subduction, intraplate, and crustal) that threaten the study area. Consequently, five earthquake records (acceleration time histories) that represent plausible subduction, intraplate, and crustal earthquakes and cover a range of duration and frequency characteristics of input motion were modeled. Dynamic material properties, which are shear strain dependent and change during excitation, were selected based on field and laboratory test results and literature (see Table 3).

Several commercially available computer programs that estimate the site effects of local geology on ground shaking are available. To identify the areas where ground shaking will be the strongest, this study used SHAKE91, which is a one-dimensional site-response analysis for vertically propagating (normally incident) shear waves at a level site (Schnable and others, 1972; Idriss and Sun, 1992).

The map incorporates the results from 15 earthquake scenarios, which include calculated amplification factors for areas (excluding bedrock) at a 300-ft grid resolution. These scenarios represent the computed results from the five earthquake time histories and three associated peak acceleration values shown on Table 1. The average amplification factor, which is applicable to the higher frequency (or shorter period) response domain, was calculated for every 300-ft cell from each of the 15 scenarios. Those factors were assigned to relative susceptibility zones as follows: a value of one or less to the lowest zone; greater than one to 1.25 to the intermediate zone; and greater than 1.25 to the highest zone.

Amplification analysis was not performed on selected areas of the map. For instance, base rock motion was assumed for most exposed bedrock areas and therefore was assigned an amplification factor of one. Higher levels of shaking, however, are assumed in steep terrain on the basis of recent research and professional judgment (Ashford and Sitar, 1994). Steep bedrock slopes and ridges may experience local topographic amplification and have been assigned a value of 1.25. Steep marine terrace slopes along the ocean bluffs have been assigned a value of 1.5. These steep bedrock and terrace areas, delineated on a 30-ft grid, were combined with the amplification layer (produced on a 300-ft grid) and cause a rough, blocky appearance on the *Amplification Susceptibility Map* (Map 2) and *Relative Earthquake Hazard Map* (Map 4).

Numerous amplification studies by researchers have generally concurred in that the motion of the surface of soft sites is greater than that at stiff sites for the same level of relatively low excitation. These studies, in a general sense, have demonstrated that assuming plane wave propagation in modeling linear one-dimensional site response for engineering purposes, such as the one used in this study, is adequate for relatively flat sites. Consequently, detailed earthquake analyses that account for three-dimensional geology, such as basin effects, and inclined and surface waves were not performed. Local topographic effects (e.g., steep slopes) and lateral changes in the materials (i.e., every 300-ft interval) were not directly modeled but were generally accommodated by the methods described above.

Two site-specific ground response analyses were performed and are presented in Appendix A (see Figure 1 for site locations). As discussed in the appendix, the calculated site-specific amplification factors are higher by up to 50 percent than those calculated in developing the amplification susceptibility map. Because both the *Amplification Susceptibility Map* and *Relative Earthquake Hazard Map* show hazard zones in "relative" terms, these site-specific results do not impact the map results. The first site, LND1, is underlain by marine terrace deposits, and the second site, LND4, by a thick deposit of alluvium. Engineering response spectra were developed from stochastically processed earthquake records representing subduction and crustal earthquakes. To conduct a complete site-specific study, a careful evaluation of the site geology and earthquake source properties, as well as of the structure under consideration in the appropriate period range, are required.

Map presentation

The *Amplification Susceptibility Map* (Map 2) depicts three zones of relative susceptibility to amplification of earthquake shaking applicable to higher frequency (or shorter period) response, as shown below. Areas within the highest susceptibility zone have been analyzed to have the greatest PGA amplification hazard.

Zone	Color	Amplification susceptibility
Zone 3	Pink	Highest.
Zone 2	Purple	Intermediate.
Zone 1	Green	Lowest. Localized amplification possible.

LANDSLIDE SUSCEPTIBILITY ANALYSIS

General

Landslides, which generally occur on steep slopes composed of weak rock or soil, can be triggered by earthquake motions, as well as other processes such as high rainfall or scour along streams. Factors controlling earthquake-induced landsliding include earthquake source and propagation path, topographic relief, groundwater conditions, material strength, vegetation, construction activities, and others. Earthquakes can activate former landslide areas or generate new slide movements. Landslides can occur during earthquake shaking or long after it has stopped and can bury extensive areas, damage structures, and destroy or block roads.

The 1949 Olympia, Washington, earthquake, which was a magnitude 7.1 (M_s) intraplate event, triggered the Narrows landslide above Puget Sound at Tacoma, Washington. The large landslide failed catastrophically along the 300-ft high bluffs three days following the earthquake and threatened nearby homes (Chleborad, 1994). Not so fortunate were the homeowners in the area of the Turnagain Heights landslide in Alaska. Triggered by the 1964 great Alaska subduction zone earthquake, this landslide extended 1,200 ft back from the face of the ocean bluff, moved land seaward over 2,000 ft, and destroyed 75 homes (Hansen, 1965; Combellick, 1993).

Methodology and discussion

The map-making methodology takes into account the following factors: slope angle, bedrock type and relative strength, existing landslides, a zone within a 1,000-ft swath of the river valleys, and moderate to steep bluffs. Slope angles, which are calculated by standard Geographic Information System (GIS) tools from the digital elevation model, are approximate and tend to be lower than actual angles (due to averaging). In selected areas with known steep slopes, such as some bedrock exposures and ocean bluffs, calculated lower slope angles have been accommodated with professional judgment. Slope factors integrated in the development of susceptibility zones were based on observations and analyses of slope angles in existing landslides versus areas of no sliding, as well as on type of bedrock, previous studies, and professional judgment.

Areas of igneous rocks, as shown on published maps, tend to sustain steeper slopes than areas of sedimentary bedrock and marine terrace deposits. Consequently, igneous rocks are assumed to have higher strength than other rock types and have been rated with lower landsliding susceptibility for a given slope.

Existing landslides, which were identified as part of this study through mapping and aerial photography analysis and supplemented with published maps, were assigned to the highest susceptibility zone. This conservative approach assumes that the slide mass has low material strength and is vulnerable to further movement. The principal factors controlling existing landslides in the study area appear to be the slope angle, nature of bedrock, and proximity to river valleys. The slopes including existing landslides were evaluated within various distances to the river valleys and appear to be less stable if within about 1,000 ft of the river valleys. This empirical observation is probably related to intersection of landslide failure surfaces with seasonally high groundwater levels. Hence, a zone within a 1,000-ft swath of river valleys and ocean bluffs have been differentiated and modeled as areas of higher hazard.

The landslide susceptibility zones were determined by use of the criteria described below. All existing landslides, igneous rock slopes 33° or greater, non-igneous slopes 26° or greater, all slopes 22° or greater within 1,000 feet of river valleys, and an approximate 60-ft swath along moderate and steep ocean bluffs were assigned to the highest susceptibility zone. Slopes 18° or greater, slopes 14° or greater within 1,000 feet of river valleys, and an approximately 60-ft swath along moderate and steep ocean bluffs adjacent to those identified in the highest susceptibility zone were assigned to the intermediate susceptibility zone. Slopes not in the highest or intermediate susceptibility zones, slopes greater than 8.5°, and all remaining bedrock slopes were assigned to the lowest susceptibility zone. Slopes less than 8.5° in terrace deposits; alluvium; and beach, bar, and dune sands are assumed to be stable.

The map indicates that there is a greater susceptibility for earthquake-induced landslide activity where slopes are relatively steep, within about 100 ft of the ocean bluffs, and in existing landslide masses. Previous studies on slope behavior in western Oregon indicate that the most common types of landslides in the local bedrock are low-volume debris flows and large, deep-seated slides (Swanson and Lienkaemper, 1985).

Technical analysis that incorporates data on material strength, ground water, and horizontal acceleration is beyond the scope of this study and was not performed. In addition, three-dimensional slope geometry, bedding, foliation, jointing, and other discontinuities, slope aspect, influences of surface water, and areas affected by human activities, such as road cuts and mine excavations, have not been specifically addressed. Landslide characteristics such as rate of movement and type of slide (such as rock versus soil, falls, rotational, translational, debris flow, and earth flows) have not been differentiated.

Map presentation

The *Landslide Susceptibility Map* (Map 3) depicts four zones of relative susceptibility to landsliding associated with earthquake shaking. Areas within the highest susceptibility zone have been analyzed to have the greatest landslide hazard and are anticipated to suffer the most intense landsliding during a significant earthquake.

Zone	Color	Landsliding susceptibility
Zone 3	Pink	Highest. May be extensive.
Zone 2	Purple	Intermediate.
Zone 1	Green	Lowest. Relatively stable. Localized landsliding possible.
Zone 0	White	None. Possible exception in small localized areas.

RELATIVE EARTHQUAKE HAZARD MAP

General

The *Relative Earthquake Hazard Map* (Map 4) integrates three separate earthquake hazard components, (1) liquefaction, (2) amplification of peak ground acceleration (PGA), and (3) landsliding, onto one composite map that generalizes the hazards. Each of these phenomena is a distinct and separate hazard. When one or more of the hazards occur in a given area, the severity of the overall hazard is increased.

The distinction between the separate hazards is important to technical specialists; thus individual hazard assessments are shown on the companion maps (Maps 1 to 3). These hazards, which were discussed above, are largely influenced by the local geologic conditions.

Methodology and discussion

Hazard areas on the individual hazard maps are divided into Zones 1, 2, and 3 (lowest to highest) with corresponding values. Areas outside these zones have been assigned a value of 0. For each 30-ft cell on the individual hazard maps, the following steps were taken: (1) the value for each hazard was squared, (2) those numbers were added together, (3) the square root was taken, and

(4) that number was rounded to the nearest whole number. Values of 4 and 5 were assigned to Zone A, which represents the highest susceptibility to earthquake hazards; a value of 3 was assigned to Zone B, which represents the range between highest and intermediate susceptibility; a value of 2 was assigned to Zone C, which represents the range between intermediate and lowest susceptibility; and a value of 1 was assigned to Zone D, which represents the lowest susceptibility for earthquake hazards.

The procedure of combining individual hazard maps to produce the *Relative Earthquake Hazard Map* was adopted to provide a single, user-friendly map for both technical and nontechnical audiences. Limitations associated with this map-making procedure stem mostly from assigning equal ratings to hazard susceptibility zones for three independent hazards and from the actual combining of the independent hazards. For example, to produce this map, areas in the highest susceptibility zone for landsliding are assigned the same rating as areas in the highest susceptibility zone to liquefaction. However, these hazard susceptibilities are not directly comparable and thus cannot be equated. In addition, ground shaking amplification of horizontal accelerations can occur below but (probably) not in liquefied soils due to the loss of strength behavior. In zones where both amplification of ground motions at the ground surface and liquefaction are hazards, combining the maps may be considered as conservative.

This map has a rough, blocky, appearance because it was created by combining the PGA amplification map (largely produced on a 300-ft grid) with the liquefaction and landslide susceptibility maps (produced on 30-ft grid).

Map presentation

The *Relative Earthquake Hazard Map* depicts four zones of susceptibility to earthquake hazards associated with ground response. Areas within the highest susceptibility zone were analyzed to have the greatest hazard and are anticipated to suffer the most intense ground response and failures during a significant earthquake.

Zone	Color	Hazard susceptibility
Zone A	Red	Highest. Intense ground response and failures possible.
Zone B	Orange	Intermediate to highest
Zone C	Yellow	Lowest to intermediate.
Zone D	White	Lowest.

COMMENTS ON HAZARD MAPS AND THEIR USES

The earthquake hazard susceptibility maps in this report have been developed for anyone concerned with earthquake hazards. Information from the maps may be used to help reduce the risk to life, injury, and property through planning policy and other mitigation measures. User groups include, but are not limited to, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens. The maps were developed as a regional planning tool and do not have site-specific accuracy.

It is possible that the information contained on the maps could be used inappropriately without careful consideration and a thorough understanding of the underlying uncertainties. The maps show trends for hazard susceptibility from the estimated response of the ground when earthquake shaking occurs. They do not include or integrate information on probability of earthquake-induced shaking or the probability of damage occurring. In addition, all areas shown on the maps are susceptible to earthquake hazards. For example, should a large earthquake occur nearby, even the "lowest" susceptibility hazard zones may be affected.

Higher susceptibility zones do not in any way suggest avoidance of the area or that an area is unsafe. The actual risk in a given area depends not only on the susceptibility zone but also on factors including land use, structure(s), nonstructural hazards, presence of hazardous materials, and other site-specific influences. Areas identified to be in higher susceptibility zones can incorporate earthquake hazards as basic information into the first steps of planning or decision making involving emergency response, mitigation, geotechnical and structural engineering, and risk level considerations.

Information provided in this publication should **NOT** be used in place of site-specific studies. The relative hazard zones are not intended to replace site-specific evaluations, such as for engineering analysis and design. Site-specific earthquake hazards should be assessed through geotechnical investigation by qualified practitioners. Site-specific evaluations may show that a site mapped in the highest susceptibility hazard zone is actually stable.

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APPENDIX

Siletz Bay area site evaluations

General

This appendix provides information on site-specific response spectra developed for two sites in the Siletz Bay study area, coastal Lincoln County, Oregon. Acceleration response spectra, such as the ones presented herein, are developed for important structures for use in design and analysis for deterministic seismic hazard assessments. These spectra are developed because behavior of structures is strongly influenced by the intensity and frequency characteristics of strong ground motions. They incorporate information on (1) earthquake ground motion, including peak ground acceleration and period or frequency of shaking, and (2) local soil conditions.

Study sites LND1 and LND4

Site-specific ground response evaluations were performed for the sites LND1 and LND4. These two sites were selected on the basis of the quality of available site-specific subsurface data and because they represent two predominant subsurface conditions within the study area. Boreholes were drilled and shear wave velocities were measured at both sites. Refer to Figure 1 in the main text for site locations and Figures A1 and A2 for subsurface data.

Site LND1, which is located at Taft Senior High School near the intersection of High School Road and Spyglass Ridge Road, has 41 ft of semiconsolidated marine terrace sands overlying bedrock. Site LND4, which is located at an abandoned section of Highway 101, immediately south of the main Siletz River channel, has 176 ft of young alluvium overlying bedrock. The alluvium consists mostly of loose sands with minor amounts of soft organic-rich clays.

Analysis

For each site, two earthquake events were considered: (1) a subduction zone earthquake located offshore, and (2) a local crustal earthquake. Two available stochastically processed earthquake records were used to evaluate these earthquake events. For each event, the mean acceleration value of the record was entered as the peak acceleration in the base rock. These input acceleration values are in general agreement with the empirical interface attenuation curves developed by Geomatrix (1995). For all site-specific studies not associated with this document, different input parameters should be determined and used to develop appropriate response spectra. Table A1 presents earthquake source input parameters used to develop the response spectra presented herein.

The subduction zone record represents an earthquake with a magnitude of 8.25 to 8.5 at a horizontal distance of 65 km. This scenario assumes that the rupture zone is located offshore either to the north or south of each site. It may be possible, however, for the rupture to occur closer to the sites than modeled. For example, if the rupture occurred directly beneath the site, the source-to-site distance and the peak ground acceleration (determined using the 1993 Geomatrix attenuation curves) would be about 20 km and 0.29 g, respectively (Geomatrix, 1995).

The crustal earthquake record represents an earthquake with a magnitude of 6 to 6.6 at horizontal distances of 0 to 25 km.

SHAKE91, which is a one-dimensional site response analysis for vertically propagating shear waves at a level site, was used to develop the response spectra (Idriss and Sun, 1992). Shear modulus reduction and damping curves, available in SHAKE91, were selected on the basis of in situ and laboratory test results, available information in geotechnical literature, and engineering judgment. Shear wave velocity data from in situ measurements were incorporated. Velocity measurements in bedrock were limited due to the presence of grout obstructing access toward the bottom of the borehole casing. For bedrock, a weighted average shear wave velocity of 2,360 ft per second (720 m/s) was used. This value was determined from the bedrock measurements available from other test locations in the study area.

Discussion

Site specific, 5-percent damped, median acceleration response spectra for subduction and crustal earthquakes with epicentral distances of 65 and 0–25 km, respectively, are provided for each site (Figures A3 and A4). The frequency content of the ground motions is influenced by the local soil conditions, as apparent in the LND1 and LND4 response spectra.

The subduction zone earthquake spectra span a wider range of periods for both sites. The thicker soil deposit at site LND4 has a damping effect for the higher frequency component of motions, tends to amplify the lower frequencies, and shifts the spectral curves from short period ground motions to longer periods. The apparent difference in these spectra illustrate the need to perform site-specific analyses to assess seismic hazards for more important structures. Amplification results and response spectra for each site are further discussed below.

Table A1. *Earthquake source input parameters*

Earthquake event	Magnitude	Horizontal distance to source zone (km)	Peak acceleration (*g*)
Subduction zone	8.25–8.5	65	0.186
Local crustal	6–6.6	0–25	0.317

Site LND1

The results of the site evaluation indicate a ground shaking amplification factor at the ground surface of 1.6 and 1.4 for the crustal and subduction earthquakes, respectively. These amplification factors are higher than the values determined for the ground shaking amplification hazard map, which fall in the 1- to 1.25-factor group, or the intermediate susceptibility category. The map analyses incorporate generalized soil properties and a wide range of ground acceleration values, while the site-specific evaluation incorporates more detailed input parameters, thus producing different results. In the site-specific case, the transition from stiffer soils at depth to softer soils near the ground surface leads to higher amplification.

The peak ordinate value on the response spectrum occurs at shorter fundamental periods, generally less than 0.4 seconds. Relatively short buildings with shorter periods would experience higher accelerations. In accordance to the 1991 Uniform Building Code (UBC), LND1 has an S1 site coefficient. Both of the response spectra exceed the UBC envelope for Zone 3 S1 at various periods.

Site LND4

The results of the site evaluation indicate that for shorter periods, damping of ground shaking will occur at the ground surface on the order of 0.6 and 0.8 for the crustal and subduction earthquakes, respectively. These damping factors are slightly higher than the 0.4 and 0.7 values determined for the ground shaking amplification hazard map, which fall in the ≤ 1 group, or the lowest susceptibility category. As previously mentioned, site-specific evaluations incorporate more detailed input parameters, and thus produce different results.

The spectral peak occurs at longer fundamental periods, generally 0.4 seconds and above. Longer period structures, such as intermediate to tall buildings and bridges, would experience higher accelerations. In accordance to the UBC, LND4 has an S3 site coefficient. Both of the response spectra, which were developed using the input parameters listed on Table A1, lie below the UBC envelope for Zone 3 S3 soils.

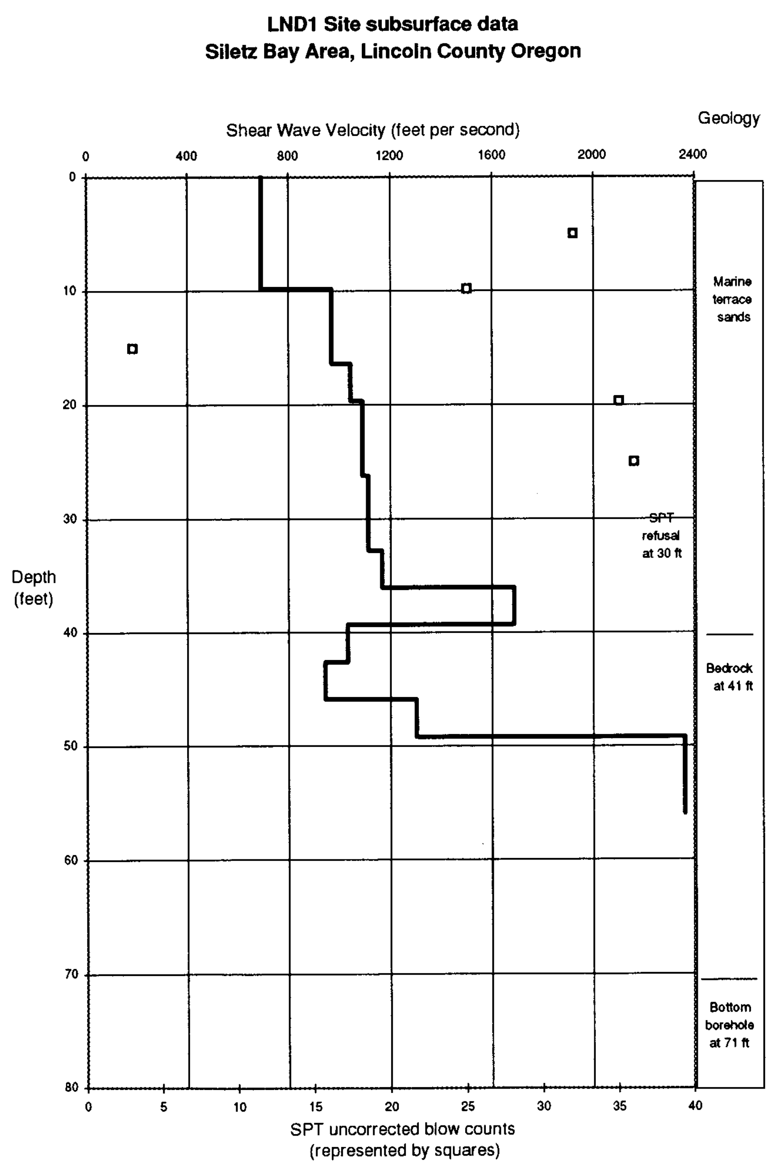

Figure A1. Subsurface data for study site LND1.

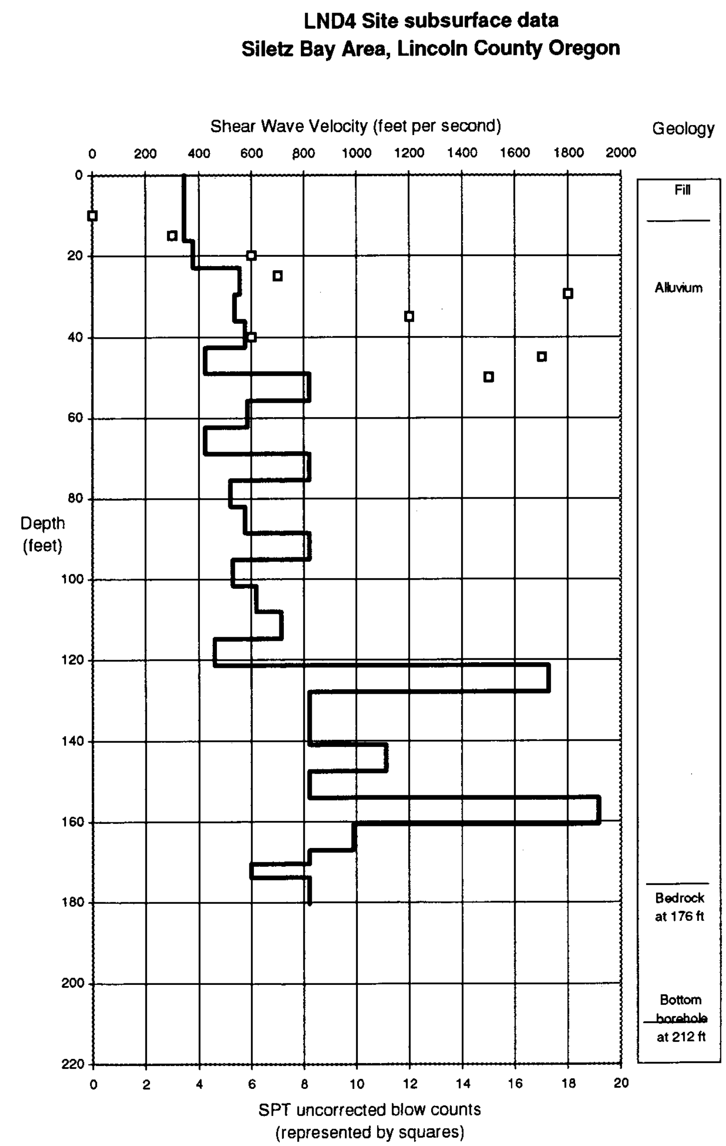

Figure A2. Subsurface data for study site LND4

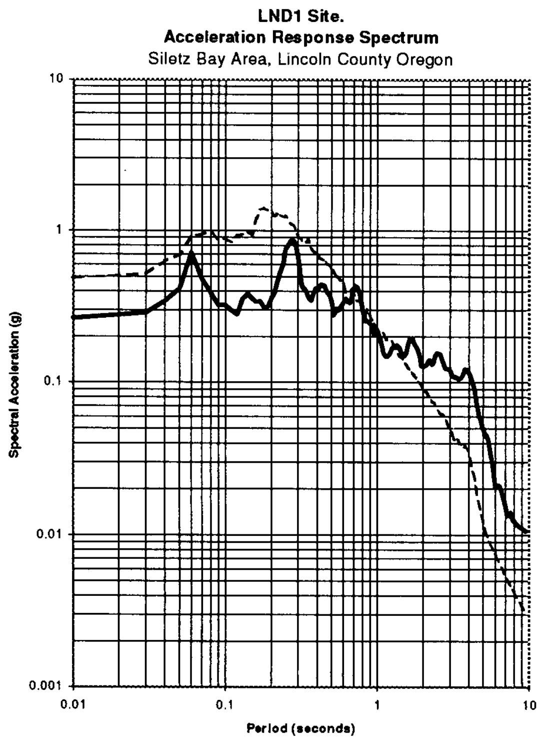

Figure A3. Acceleration response spectrum, study site LND1, for subduction earthquake (solid line) and local crustal earthquake (broken line). Damping ratio = 5 percent.

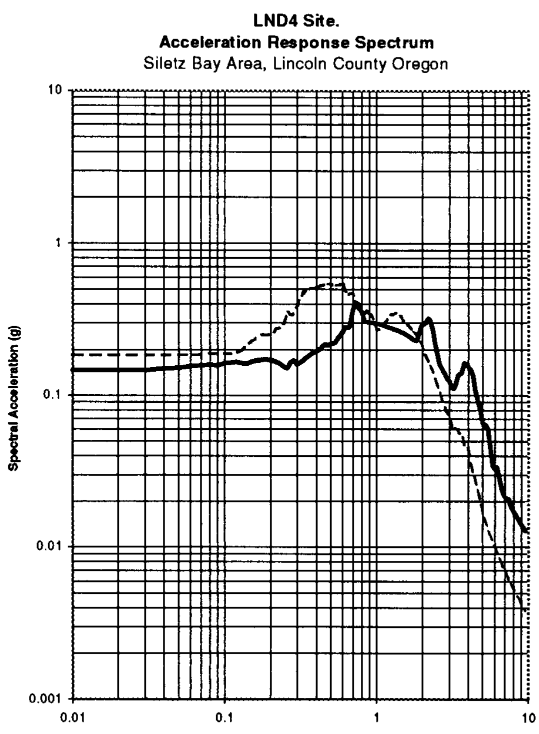

Figure A4. Acceleration response spectrum, study site LND4, for subduction earthquake (solid line) and local crustal earthquake (broken line). Damping ratio = 5 percent.