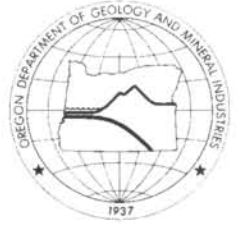


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Style is generally that of U.S. Geological Survey publications. (See USGS *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) Bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Include names of reviewers in the acknowledgments.

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, letters, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office (address above).

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## Cover photo

Aerial view of rockfall that occurred on Oregon's coastal Highway 101 about 2 mi north of Manzanita in Tillamook County on October 23, 1994. A second rockfall scar, to the right (south), is from a rockfall in January 1994. The events that originated in highly jointed Miocene gabbro both caused extended closures of the highway and hundreds of thousands of dollars in damage.

The Oregon Department of Transportation initiated an intensive evaluation of the stability of the section of the road cut that includes the rockfall sites and is between 80 and 200 ft high. A staged mitigation program was developed: Preliminary rock scaling (removal of loose rock) was performed immediately, and a comprehensive hazard reduction program is proposed for late 1995. Oregon Highway Division photo by Bergman Photographic Services, Portland. Photo and text courtesy Dan Meier, Woodward-Clyde Consultants, Portland.

## Information center expanded

The Nature of the Northwest Information Center, operated jointly by the State of Oregon natural resource agencies and the USDA Forest Service, opened on December 5, 1994, on the first floor of the State of Oregon Office Building at 800 NE Oregon Street in Portland. It replaces the Nature of Oregon Information Center, which had been operating at the 800 NE Oregon Street location since 1992. Hours of the new center are 8:00 a.m. to 5:00 p.m. on weekdays. The phone number is 503-872-2750, and fax number is 503-731-4066.

Numerous publications, including a wide selection of maps, books, and brochures designed to enhance an experience in the great outdoors, are available at the Center. An expanded staff is available to respond to phone, fax, and mail inquiries. "Visitors to the new Nature of the Northwest Information Center are able to obtain a vast range of information about natural, cultural, and outdoor recreational resources in Oregon and Washington in a centrally located, 'one-stop shopping' environment," says John Lowe, Regional Forester, USDA Forest Service.

Located centrally in Portland near Interstate Highways I-5 and I-84 and the 7th Ave. stop of MAX, three blocks east of the Convention Center, and three blocks south of the Lloyd Center, the Nature of the Northwest Information Center is ideally situated to serve both Oregonians and visitors to the area. "This partnership between the USDA Forest Service and the State of Oregon enables us to serve our customers more efficiently," says Don Haines, manager of the Nature of the Northwest Information Center, who anticipates adding new services to the center because of the partnership. □

## Madin transferred to Baker City office

Ian P. Madin, Earthquake Geologist for the Oregon Department of Geology and Mineral Industries (DOGAMI), has been transferred from the Portland area to DOGAMI's field office in Baker City. He began his new duties in Baker City on November 21. Madin spearheaded DOGAMI's early work with Metro to alert Oregonians to the potential hazards posed by earthquakes and helped develop the DOGAMI program for determining relative earthquake hazards based on liquefaction, ground motion amplification, and slope stability. He will be using his considerable expertise on earthquakes to round out DOGAMI's earthquake program in eastern Oregon, which covers two-thirds of the state. He will be working with Mark Ferns, DOGAMI's Baker City Regional Geologist, to map and identify faults in eastern Oregon.

In addition to his new duties, Madin will continue to perform as part of DOGAMI's earthquake team. Work in western Oregon will be continued by DOGAMI's earthquake specialists Matthew Mabey, Mei Mei Wang, and Jerry Black, who are currently completing relative earthquake hazard maps for the Portland area, conducting relative earthquake hazard studies in the Salem area, and completing catastrophic earthquake hazard studies in the greater Siletz Bay area along the coast. George Priest is spearheading cooperative assessments of tsunami risk along the Oregon coast. □

## BLM State Office moved to new location

The Bureau of Land Management Oregon/Washington State Office has moved to the 1515 Building at 1515 SW 5th Avenue between Clay and Market Streets in downtown Portland. Parking is available for visitors on the first floor of the parking garage located within the building, and members of the public can receive parking validation in the public room located on the 7th floor. Mail should be addressed as before to P.O. Box 2965, Portland, OR 97208-2965. For further information, call BLM's public information line at (503) 952-6002, the public room at (503) 952-6001, or public affairs at (503) 952-6027. □

# Magnitude and frequency of subduction-zone earthquakes along the northern Oregon coast in the past 3,000 years

by Mark E. Darienzo and Curt D. Peterson, Department of Geology, Portland State University, P.O. Box 751, Portland, Oregon 97207

## ABSTRACT

Similarities in number, depth, sequence stratigraphy, and radiocarbon ages characterize buried peats of seven estuaries along 175 km of the northern Oregon coast. We use these peats to infer the extent of earthquake-induced subsidence, earthquake magnitudes, and average recurrence intervals for late Holocene earthquakes at the Cascadia Subduction Zone. Synchronicity of earthquake-induced subsidence from Alsea Bay to the Necanicum River over a coastal distance of 175 km is inferred most confidently for the most recent (first) event and the third through sixth events. In contrast, earthquake-induced subsidence for the second event was lacking in at least three of the seven estuaries. However, tsunamis generated by the second event deposited sands in the unsubsided estuaries. Therefore, the second event is also considered synchronous between Alsea and Necanicum. A segment boundary between Yaquina and Netarts is inferred for the second event.

From these findings of synchronicity, we estimated the length of rupture for the late Holocene earthquakes. The corresponding magnitudes are at least 8.0, based on a rupture length of 175 km, a rupture width of at least 60 km, an average recurrence interval of 400 years, an average convergence rate of 4 cm/yr, and a shear modulus of  $3 \times 10^{11}$  dynes/cm<sup>2</sup>. Using a range of convergence rates (3.5–4.5 cm/yr) and average recurrence intervals (300–500 years), rupture lengths (105–175 km), and rupture widths (60–90 km), calculated magnitudes for five of the last six earthquakes are greater than 8.0 for the central 175 km of the Cascadia Subduction Zone.

Average recurrence intervals between earthquakes for the estuaries on the northern Oregon coast range between 200 and 600 years. The wide range is due to the uncertainties associated with radiocarbon ages. Although more accurate recurrence intervals are desirable, these average recurrence intervals provide a useful estimate for assisting coastal communities with their disaster planning and for determining probabilities for future subduction-zone earthquakes off the northern Oregon coast.

## INTRODUCTION

In the past ten years, several geophysicists have called attention to the potential for great earthquakes (greater than magnitude 8) related to the Pacific Northwest subduction-zone known as the Cascadia Subduction Zone (Heaton and Hartzell, 1987; Savage and Lisowski, 1991; Hyndman and Wang, 1993) (Figure 1). Although there have been large (up to magnitude 7.5) earthquakes in the region during historic times (last 150 years), there is no historical record of Pacific Northwest subduction-zone earthquakes, which are often greater than magnitude 8—with the possible exception of the 1992 Cape Mendocino earthquake (G. Carver, personal communication, 1994). However, evidence for subduction-zone earthquakes in the late Holocene has been found in the deposits of coastal wetlands of estuaries in British Columbia, Washington, Oregon, and northern California (Atwater, 1987, 1992; Darienzo and Peterson, 1990; Peterson and Darienzo, 1991; Clarke and Carver, 1992; Nelson, 1992a; Clague and Bobrowsky, 1994; Darienzo and others, 1994).

Now that subduction-zone earthquakes have been recognized in the stratigraphic record, questions arise as to what are the magnitudes of these Holocene earthquakes and the frequency with which they occur. Knowledge of the magnitudes and frequency is necessary to calculate the probability of the next earthquake and to help communities with disaster planning and the building of new and upgrading of existing structures.

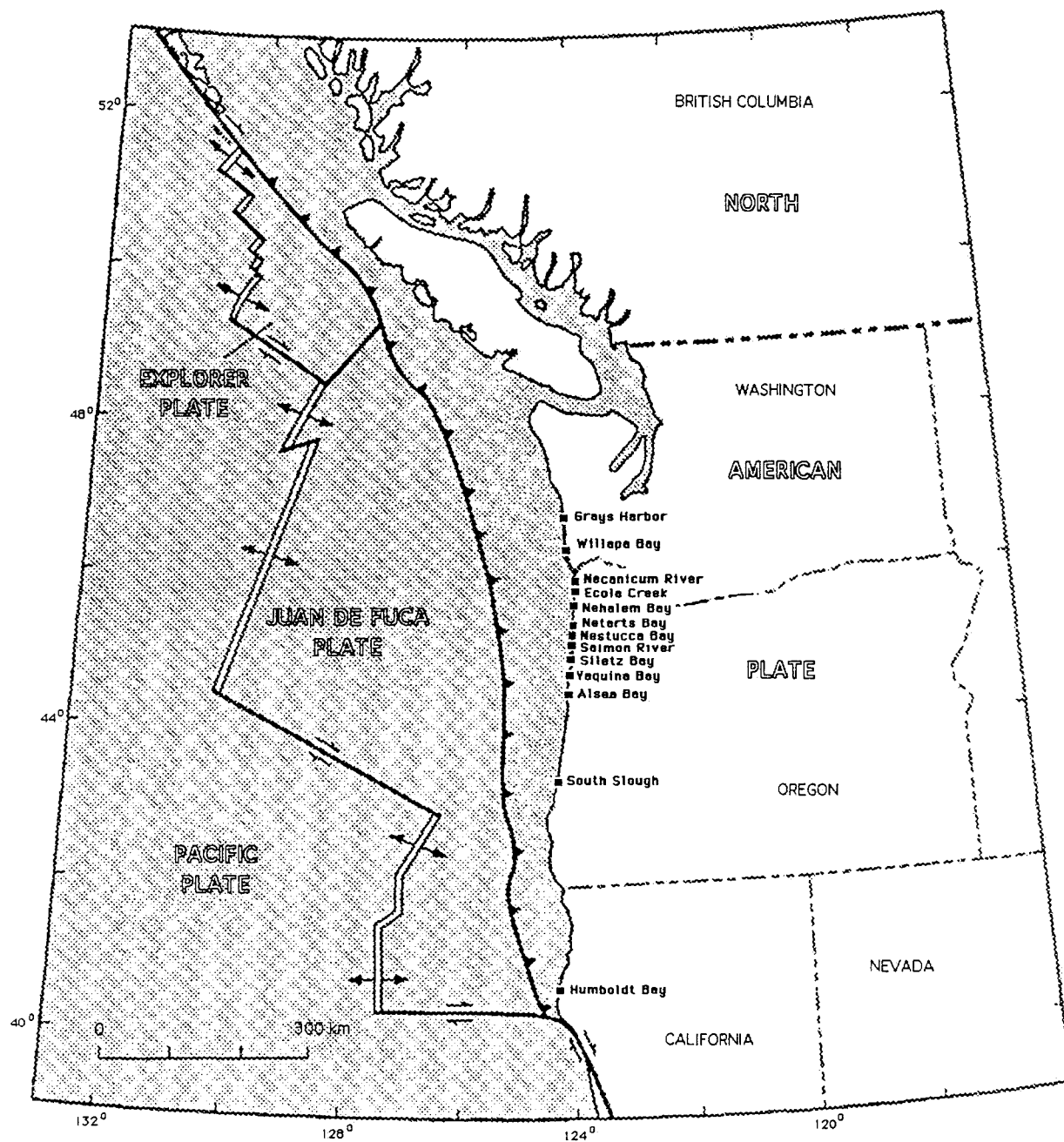
In this study, we compare the stratigraphy and associated radiocarbon ages of seven estuaries along the northern Oregon coast: at Alsea Bay, Yaquina Bay, Siletz Bay, Nestucca Bay, Netarts Bay, Ecola Creek, and Necanicum River—an along-coast distance of 175 km (Figure 1). We selected these estuaries because we have made detailed studies of marsh stratigraphy at each of them. Results have been published for Alsea by Peterson and Darienzo (1991); for Netarts by Darienzo and Peterson (1990) and Darienzo (1991); for Yaquina, Siletz, Nestucca, and Necanicum by Darienzo (1991), Darienzo and others (1993), and Darienzo and others (1994); and for Ecola by Gallaway and others (1992). Stratigraphic patterns and radiocarbon ages were used to calculate possible ranges for paleomagnitudes and average recurrence intervals. These results can potentially be compared with similar patterns and ages of paleoseismic events recorded in estuaries of other segments of the Cascadia Subduction Zone.

## ESTIMATION OF MAGNITUDE

### Establishment of event synchronicity

We used the late Holocene stratigraphic records in individual estuaries to assess the synchronicity of the paleoearthquakes among the estuaries along the northern Oregon coast. In this study, we examined and compared the following stratigraphic patterns in the paleoseismic record: the number and stratigraphic location of inferred tsunami deposits and the number, age, and stratigraphic position (depth) of earthquake-buried peats recorded within a specific period of time. If the events are synchronous, the magnitudes of the Holocene earthquakes can be estimated for rupture segments of at least the length of the northern Oregon coast. Synchronicity of coseismic events between estuaries provides information on the length of earthquake rupture along the coast. Therefore, the rupture length, as determined by synchronicity of events, would be a key parameter in paleomagnitude determinations. Formulas that use rupture length (coastline distance of event synchronicity) and estimates of rupture width and seismic slip could then be used to describe paleoearthquakes (Kanamori, 1977; Abe, 1981, 1984; Rogers, 1988; Byrne and others, 1990; Geomatrix, 1993).

A possible alternative to synchronicity of events along the northern Oregon coast is segmentation. In other words, ruptures occur along smaller segments of the locked subduction zone at different times, producing earthquakes of lesser coastline extent and magnitude. For example, a pair of earthquakes off Japan in the Nankai Trough resulted from rupture of adjacent segments in 1944 and 1946, while the 1707 Nankai Trough earthquake resulted from rupture of both segments simultaneously (Ando, 1975). The use of prehistoric dating, no matter how sensitive the dating technique, could not conclusively prove earthquake synchronicity because of the range of possible ages associated with conventional radiocarbon ( $\pm 100$  yrs), high-precision radiocarbon ( $\pm 10$  years), or dendrochronology ( $\pm 10$  years) (Yamaguchi and others, 1989). However, synchronicity of the 300-yr-B.P. (before present) paleoseismic event between widely separated estuaries is suggested by similarities between high-precision radiocarbon ages and tree-ring ages of buried trees in coastal wetlands of Washington, Oregon, and northern California (Yamaguchi and others, 1989; Atwater and others, 1991; Carver and others, 1992; Nelson and Atwater, 1993). Further evidence for synchronicity has come from similarities in stratigraphic patterns of marsh deposits. For example, Atwater (1992) inferred correlations largely on the basis of appear-






-  Seaward edge of plate boundary--Barbs show direction of dip
-  High-angle fault--Arrows show strike slip
-  Spreading ridge

Figure 1. Cascadia Subduction Zone and northern Oregon estuaries. Distance between the Necanicum and Alsea estuaries is approximately 175 km.

ance and stratigraphic position of buried soils among estuaries on the southern Washington coast.

Other stratigraphic criteria, such as the number and position of tsunami sands, might also be useful in synchronicity determinations. If the northern Oregon coast ruptured as one segment during the earthquakes, one would expect a one-to-one correspondence of buried peats to overlying tsunami deposits and a similar number of tsunami deposits within each of the individual estuaries. If the northern Oregon coast ruptured in smaller segments, then some estuaries should contain more tsunami sand layers than buried peats, because tsunamis produced in adjacent ruptured segments would propagate to unruptured segments and deposit sands in estuaries that did not experience coastal subsidence. In contrast, if all of the estuaries contained only one tsunami layer for each recorded subsidence event, then there would be no evidence for segmentation of the margin (Peterson and Darienzo, 1991). However, earthquakes that occur less than one year apart and in adjacent segments would be difficult to tell apart in the geologic record. Marsh plants might not have become sufficiently reestablished above the tsunami sand to leave a peat record prior to deposition of the next tsunami sand. In estuaries with slow sedimentation rates, sediments may take decades to accumulate in sufficient quantities to be distinguishable in the stratigraphic record and thus allow differentiation between separate tsunamis. Therefore, the two events might not be sufficiently distinguishable to indicate segmentation. In summary, a similar number of tsunami sands and a one-to-one correspondence of tsunami sands with peats (buried due to coseismic subsidence and postseismic sedimentation) in several estuaries suggests synchronicity of earthquakes among adjacent estuaries.

#### Calculating paleomagnitude

We estimated earthquake magnitudes in two ways. First, we estimated the moment magnitude ( $M_W$ ) of an earthquake by using the equation  $M_W = 2/3 \times \log_{10} M_0 - 10.7$  (equation 1) (Kanamori, 1983).  $M_0$  is the seismic moment and is equal to the product of the area of rupture, the amount of slip along the fault, and a constant called the shear modulus, which is a measure of a rock's ability for or resistance against deformation when stressed. We assumed a shear modulus of  $3 \times 10^{11}$  dynes/cm<sup>2</sup>, a value used to calculate the magnitude of the 1960 Chilean and 1964 Alaskan subduction-zone earthquakes (Kanamori and Anderson, 1975). Second, we used the equation  $M = \log A + 3.99$  (equation 2), where  $A$  is the area of rupture (Abe, 1981, 1984).

To use both magnitude equations, we made further assumptions:

(1) Equation 1 requires an average slip per event that can be estimated from recurrence intervals of coseismic subsidence events and the rate of convergence (approximately 4.0 cm/yr) of the Juan de Fuca plate with the North American plate (Riddiough, 1977). For the calculations in this paper, we assumed the seismic slip to be 90 percent of the total, with the remaining 10 percent considered aseismic (Rogers, 1988).

(2) Both equations require a rupture width that comes from (a) other subduction zones that have characteristics similar to the Cascadia Subduction Zone (approximately 100 km, according to Rogers, 1988) or (b) estimated rupture widths for the Cascadia Subduction Zone. Savage and Lisowski (1991) estimated a rupture width off the northern coast of Washington of at least 100 km. A two-dimensional dislocation fit model of coseismic vertical movement for the central Cascadia Subduction Zone was run by J. Savage (U.S. Geological Survey, Menlo Park, California), who used subsidence estimates of marsh burial events from northern Oregon and calculated a rupture width of 90 km for Oregon (Peterson and others, 1991). Clarke and Carver (1992) estimated a rupture width of 70–80 km for the Gorda segment of the Cascadia Subduction Zone. Hyndman and Wang (1993) estimated a 70-km locked zone for Oregon on the basis of predicted temperatures on the thrust plane. Finally, in central Oregon a locked zone of 60 km was estimated, in one case

by use of a change in orientation of upper plate deformation on the Oregon continental margin (outer edge of the locked zone) (Goldfinger and others, 1992) and in another case on the basis of an apparent position of the zero isobase at the coast (inner edge of the locked zone) (Peterson and Darienzo, 1991). The 60-km locked zone is thought by these authors to represent the minimum rupture width for a Cascadia Subduction Zone earthquake occurring off the northern Oregon coast. Therefore, from the above information, an approximate rupture width would range from 60 km to 90 km for the northern Oregon coast.

#### FREQUENCY OF EARTHQUAKES

In this study, we used radiocarbon ages of samples taken from the stratigraphic record of earthquakes in seven estuaries on the northern Oregon coast to calculate average recurrence intervals for Holocene earthquakes in the last 3,000 years (Figure 2). In calculating the average recurrence intervals for each estuary, we used only the last six inferred earthquakes in each estuary, because the preservation potential of buried peats diminishes over time, due, in part, to erosion by migrating tidal and river channels. The age of the youngest buried peat was subtracted from the age of the oldest buried peat and divided by the number of intervals between the oldest and youngest events. For example, if the oldest buried peat yielded a radiocarbon age of 3,000 years B.P. and the youngest 300 years B.P. and there were five intervals in between, then the average recurrence interval is 540 years.

The actual age of each buried peat falls within a range of values based on two standard deviations ( $2\sigma$ ), a range in which there is a 95-percent chance that the age of the peat falls within that range. Therefore, the average recurrence intervals will also fall within a range of values. We used an error multiplier of two to insure that the actual radiocarbon age of the buried peat is included within the range of values (B. Atwater, personal communication, 1994). The range was calculated by quadrupling the laboratory error and adding and subtracting that value to and from the raw radiocarbon age. For example, if the raw radiocarbon age is  $400 \pm 60$ , then 240 is added to and subtracted from 400 to produce a range of 160–640. We also calculated calibrated ages from raw ages, using the computer calibration program of Stuiver and Reimer (1986). The ranges of calibrated ages (only those values used to calculate recurrence intervals) are included in Table 1 along with the raw radiocarbon ages and the age ranges calculated with the methods described in this paper.

The lowest value of the average recurrence interval range is determined by subtracting the greatest age of the youngest event from the smallest age of the oldest event and dividing by the number of intervals between inferred earthquakes. The highest value is determined by subtracting the smallest age of the youngest buried peat from the largest age of the oldest buried peat and dividing by the number of intervals between inferred earthquakes. For example, if the age range of the youngest buried peat is 200–500 radiocarbon-calibrated years B.P. and the age range of the oldest buried peat is 2,900–3,200, then the average recurrence interval ranges from 480 to 600 years.

The ages of the earthquakes were determined from peat samples taken from the top 5–10 cm of the buried peat. These ages represent the maximum ages of the earthquakes unless the peat is contaminated with younger descending roots. Given no contamination, the actual age of an earthquake is therefore younger than the age of the buried peat. However, this should not create any further systematic errors in average recurrence interval calculations.

Different materials taken from the same depth within the same peat can differ in radiocarbon age by hundreds of years (Nelson, 1992b). Dating bulk peat samples from the top 5–10 cm of the peat horizon (almost all radiocarbon ages in this study) could average out these differences. However, the range of ages for individual samples of peats can be greater than the recurrence interval calculated for

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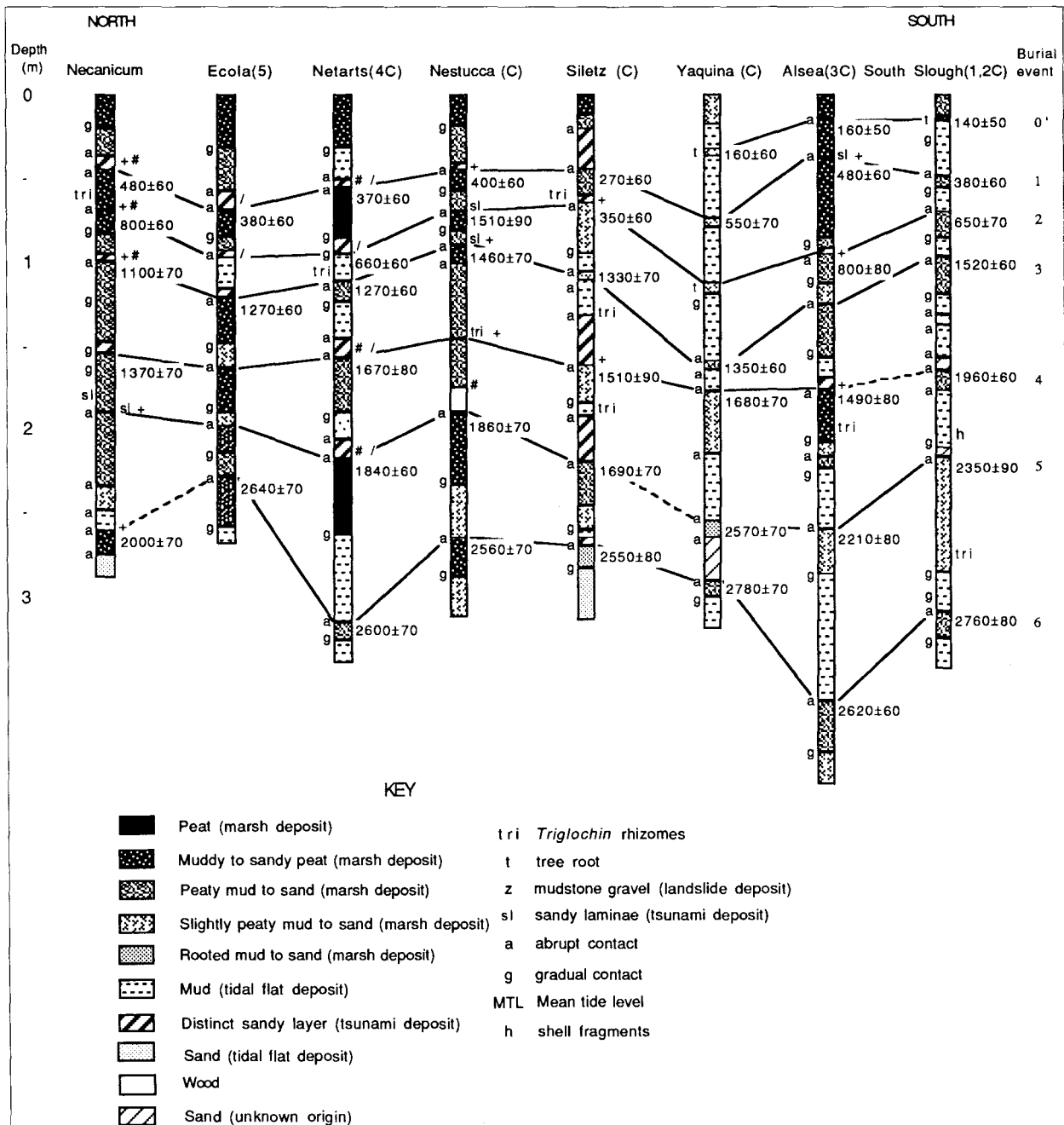


Figure 2. Representative stratigraphic columns with evidence for subduction-zone earthquakes and radiocarbon ages for all estuaries studied along the northern Oregon coast as well as South Slough, an estuary at Coos Bay on the south-central Oregon coast. Necanicum, Nestucca, Yaquina, and South Slough stratigraphic columns are composites. “#” indicates an increase or first appearance of brackish or marine diatoms from the buried peat to overlying sediments; “+” indicates an increase or first appearance of beach sand from the peat to overlying sediments; “/” indicates >50 percent beach sand in a probable tsunami deposit above the peat. Unnumbered stratigraphic columns are from Darienzo (1991) and Darienzo and others (1994). Columns numbered 1–5 are from (1) Nelson (1992b), (2) Peterson and Darienzo (1989), (3) Peterson and Darienzo (1991), (4) Darienzo and Peterson (1990), and (5) Galloway and others (1993). “C” indicates that column is a composite of two or more sites.

Table 1. Radiocarbon ages of materials (peats unless otherwise noted) from estuaries along the northern Oregon coast that have produced evidence for Holocene subduction-zone earthquakes

Estuary (sources)	Site, location	Depth in cm (burial event no.)	Age in radiocarbon yrs B.P.	Age range in yrs B.P. 2 error multiplier (Cal. age range at 2 $\sigma$ )	Laboratory no. (Beta)
Necanicum (Darienzo and others, 1994)	Neawanna 2, UTM428900, 5092300, zone 10, N	48 (1)	480 $\pm$ 60	240-720 (300-680)	42112
		70 (2)	800 $\pm$ 60	560-1,040	42113
		111 (3)	1,100 $\pm$ 70	820-1,380	42088
		158 (4)	1,370 $\pm$ 70	1,090-1,650	44595
		268 (6)	2,000 $\pm$ 70	1,720-2,280 (1,610-2,340)	42114
	Neawanna 5, UTM 428900, 5092600, zone 10, N	78 (2)	680 $\pm$ 80	360-1,000	43127
		167 (6)	2,200 $\pm$ 90	1,840-2,560	42115
	Ecola (Gallaway and others, 1992)	70 (1)	380 $\pm$ 60	140-620 (0-590)	56402
		120 (3)	1,270 $\pm$ 60	1,030-1,510	56401
		230 (6)	2,640 $\pm$ 70	2,360-2,920 (2360-3050)	56404
Netarts (Darienzo and Peterson, 1990; Darienzo, 1991)	5, UTM 424400, 5024200, zone 10, N	55 (1)	370 $\pm$ 60	130-610 (0-578)	24933
		111 (3)	1,270 $\pm$ 60	1,030-1,510	24934
		157 (4)	1,670 $\pm$ 80	1,350-1,990	24520
		220 (5)	1,840 $\pm$ 60	1,600-2,080 (1490-2030)	24521
		316 (6)	2,600 $\pm$ 70	2,320-2,880 (2360-3050)	41668
	Oyster farm, UTM 426800, 5029900, zone 10, N	97 (2)	660 $\pm$ 60	420-900	41638
	Nestucca (Darienzo and others, 1994)	80 (1)	400 $\pm$ 60	160-640 (0-620)	43123
Siletz (Darienzo and others, 1994)	Nestucca Duck, UTM 425500, 5004200, zone 10, N	70 (2)	1,510 $\pm$ 90	1,150-1,870	42000
		90 (3)	1,460 $\pm$ 70	1,180-1,740	42084
		190 (5)	1,860 $\pm$ 70	1,580-2,140 (1,460-2,110)	41637
		266 (6)	2,560 $\pm$ 70	2,280-2,840 (2,320-2,920)	41671
	Salishan House, UTM 418700, 4971500, zone 10, N	47 (1)	270 $\pm$ 60	30-510 (0-520)	42089
		67 (2)	350 $\pm$ 60	110-590	42090
		163 (4)	1,510 $\pm$ 90	1,150-1,870	42001
		220 (5)	1,690 $\pm$ 70	1,410-1,970 (1,310-1,900)	42091
		273 (6)	2,550 $\pm$ 80	2,230-2,870 (2,200-2,970)	42002
	Millport Slough 1, UTM 421500, 4970800, zone 10, N	48 (1)	480 $\pm$ 60	240-720 (300-680)	42085
		135 (3)	1,330 $\pm$ 70	1,050-1,610	43126
		159 (4)	1,630 $\pm$ 70	1,350-1,910	43125
		210 (5)	1,850 $\pm$ 70	1,570-2,130 (1,440-2,100)	42086
	Yaquina (Darienzo and others, 1994)	30 (0')	160 $\pm$ 60	0-400	41991
Alsea (Peterson and Darienzo, 1991)	Outcrop B, UTM 428300, 4938400, zone 10, N	77 (1)	550 $\pm$ 70	270-830 (310-720)	38862 (wood)
	Slack 1, UTM 427800, 4938000, zone 10, N	62 (3)	1,350 $\pm$ 60	1,110-1,590	42092
		81 (4)	1,680 $\pm$ 70	1,400-1,960	42093
		160 (5)	2,570 $\pm$ 60	2,330-2,810 (2,340-2,890)	42094
		196 (6)	2,780 $\pm$ 70	2,500-3,060 (2,530-3,260)	42095
	Outcrop, UTM 419500, 4918700, zone 10, N	50 (1)	480 $\pm$ 60	240-720 (300-680)	39181 (wood)
South Slough	AB 8, UTM 419000, 4918800, zone 10, N	87 (2)	800 $\pm$ 80	480-1,120	27184
		177 (4)	1,490 $\pm$ 80	1,170-1,810	26791
		242 (5)	2,210 $\pm$ 80	1,890-2,540 (1,830-2,710)	27185
		327 (6)	2,620 $\pm$ 60	2,380-2,860 (2,370-2,960)	26792
	Winchester 12, UTM 3931000, 4792400, zone 10, N (Nelson, 1992b)	47 (1)	380 $\pm$ 60	140-620 (0-590)	26289
	Day Creek, UTM 393800, 4796500, zone 10, N (Peterson and Darienzo, 1989)	15 (0')	140 $\pm$ 50	0-340 (0-450)	41639 (wood)
		72 (2)	650 $\pm$ 70	370-930	27675
		98 (3)	1,520 $\pm$ 60	1,280-1,760	34280
		167 (4)	1,960 $\pm$ 60	1,720-2,200	27744
		220 (5)	2,350 $\pm$ 90	1,990-2,710 (1,920-2,800)	27743
		310 (6)	2,760 $\pm$ 80	2,440-3,080 (2,440-3,300)	34278



repeated earthquakes. This suggests that conventional radiocarbon dating is poorly suited for determining individual recurrence intervals at the Cascadia Subduction Zone (Nelson 1992b). A more accurate estimate of the age of an earthquake can be obtained from the dating of matter that was killed as a result of the earthquake, such as tree roots or herbaceous leaves in growth position (Nelson and Atwater, 1993). This method avoids the problems associated with dating bulk peat and also narrows the range of individual radiocarbon ages and average recurrence intervals. Although more accurate recurrence intervals are desirable, the average recurrence intervals calculated here will provide a useful estimate for hazard planning.

## RESULTS AND DISCUSSION

### Synchronicity of events

The stratigraphy in each estuary records six burial events associated with subduction-zone earthquakes during the last ~3,000 years. The buried peats that identify the events are usually found in the top 3 m. Figure 2 compares stratigraphy between the estuaries with respect to depth below the modern marsh surface, using representative cores from each estuary.

The depth to the tops of the buried peats for the last six events is similar among estuaries and falls within distinct ranges (Figure 3). This depth consistency possibly reflects a similar response by the marshes to coseismic subsidence and postseismic burial within the framework of eustatic sea-level rise in the late Holocene. Nontectonic burial of marshes with sediment from floods or storm surges would not be consistent between estuaries over 175 km of coastline because of the greater variability of effects from rainfall and storm activity along the coast. Major storms and floods occur much more frequently than subduction-zone earthquakes. Thus, buried peats would be more abundant in the stratigraphic record of coastal marshes if storms and floods were included as causes of marsh burial. Therefore, the consistency in depth and number of buried peats among estuaries on the northern Oregon coast in the last 3,000 years favors a burial mechanism of coseismic subsidence and postseismic sedimentation from subduction-zone earthquakes. The ranges in depth for each event are probably the result of differences

in the amount of subsidence, the postseismic sedimentation rate, the rate of postseismic rebound, and eustatic sea-level rise.

The range of radiocarbon ages for each of the six buried peat horizons is fairly consistent among estuaries (Figure 4). A few events have no radiocarbon ages, because the peat was not dated (Darioenzo and others, 1994). The radiocarbon age of one event from the Hurliman site at Nestucca was excluded because of the inconsistency of its age in relation to the ages above and below (event 4: 3,113–3,619 cal.  $^{14}\text{C}$  yrs B.P.). Similarity in age ranges among buried peats supports synchronicity of events among the estuaries. However, not all buried peat age ranges overlap at  $2\sigma$  (95-percent confidence that the age of the peat is within the range). Based solely on radiocarbon dating, past subduction-zone earthquakes along the northern Oregon coast could have been either subduction-zone earthquakes that occurred synchronously among all estuaries on the northern Oregon coast or subduction-zone earthquakes that occurred among estuaries within two or more segments. Nevertheless, the radiocarbon dating shows that a similar number of earthquakes occurred within similar time intervals throughout the northern Oregon coast.

Three to five tsunami sand layers have been deposited in each estuary within the last 3,000 years. Almost all sand layers immediately overlie buried peats, which is indicative of earthquake subsidence and tsunami deposition. The sand layers of the second event in at least the three northernmost estuaries do not overlie buried peats, because the sands are not associated with subsidence in those areas. This consistency in numbers of tsunami sands among the estuaries, along with the almost one-to-one correspondence of tsunami sands with subsidence, supports synchronicity of the events between Alsea and Necanicum.

The evidence for synchronicity among estuaries along the northern Oregon coast will be discussed separately for each event.

The **first (youngest) burial event** appears to have been the most consistent and clearly represented event with respect to age and presence of tsunami-deposited sands in all the northern estuaries (Figures 2–4) (Darioenzo and others, 1994). The representative stratigraphy and radiocarbon ages of the Yaquina Bay estuary in Figure 2 are from sites in the upper reaches of the estuary and do not contain tsunami sands above any of the six buried peats. However, tsunami sands overlie the youngest peat at sites in the lower to middle reaches of that estuary (Figure 2) (Darioenzo and others, 1994; Peterson and Priest, in preparation). A relatively young burial event in the lower reaches ( $160 \pm 60$   $^{14}\text{C}$  yrs B.P. and 0–310 cal.  $^{14}\text{C}$  yrs B.P.) was identified as a separate event (0') by Darioenzo and others (1994), based on radiocarbon age, depth, and comparison with similar horizons in Alsea Bay and South Slough (Figure 2). However, this 0' designation is very tentative. The 0' age could possibly represent this first event at all three estuaries, based on age overlap at  $2\sigma$ . The younger ages could also be due to descending modern roots that were incorporated into the uppermost peat (Figure 4). For example, buried horizons with radiocarbon ages of 380 and 140 years B.P. at South Slough could signify the same burial event rather than two separate events, even though they are from two different sites (Figure 2). Based on ages, evidence of subsidence (Darioenzo and others, 1994), and one-to-one correspondence of tsunamis with subsidence, the first event probably occurred synchronously among the estuaries on the northern Oregon coast.

The **second burial event** is characterized by (1) tsunami sand and lack of subsidence evi-

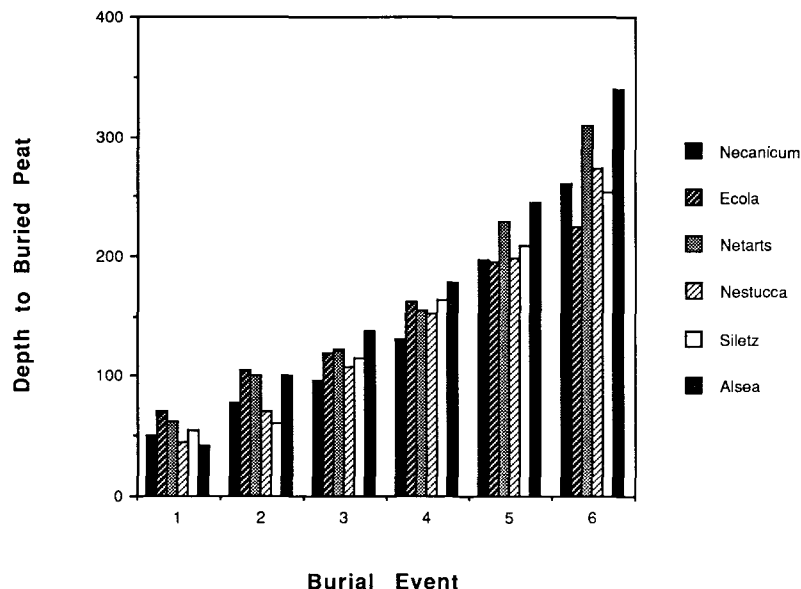


Figure 3. Depths to the tops of buried peats for the last six earthquakes in six of the seven estuaries discussed. Yaquina is excluded, because events from two sites were combined to create composite stratigraphy. From Darioenzo and others (1994).



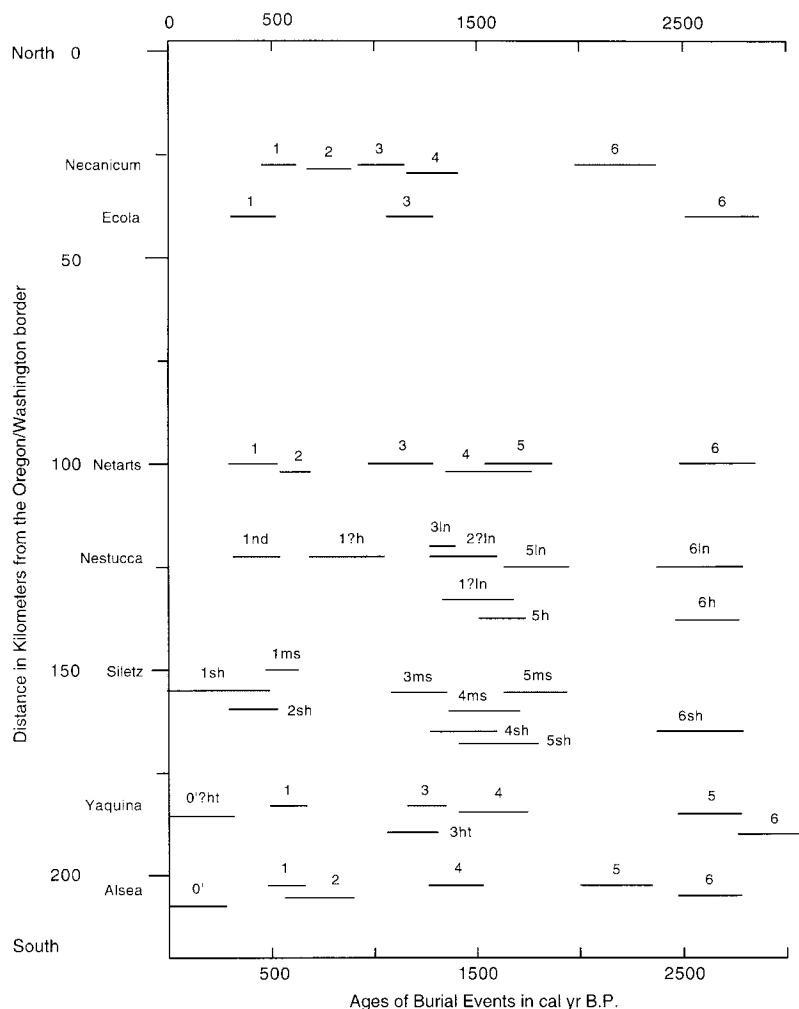


Figure 4. Ranges of calibrated radiocarbon ages with two deviations ( $2\sigma$ ) of the last six earthquake events for all estuaries. Numbers designate events. Question marks indicate event designation uncertainties. Lower-case initials designate specific sites within the estuary where materials were radiocarbon dated (nd = Nestucca duck; ln = Little Nestucca; h = Hurliman; sh = Salishan House; ms = Millport Slough; ht = Hatfield). See Darienzo and others (1994) for stratigraphy of the Nestucca and Siletz cores.

dence in Netarts, Ecola, and possibly Necanicum; (2) tsunami sand and subsidence in Alsea, Nestucca, and Yaquina; and (3) tsunami sand at several sites and possible evidence of subsidence at a few sites in Siletz Bay (Figure 2) (Darienzo and others, 1994; Peterson and Darienzo, 1994; Peterson and Priest, in preparation). Age control for the second event is weak. The ages of the buried peats for the second event overlap at  $2\sigma$  for Necanicum, Netarts, and Alsea (Figure 4). However, the age from Nestucca is much older than these, and it is not clear if this event, documented at four estuaries in northern Oregon, affected Nestucca Bay. The age of the second buried peat at Nestucca might be suspect and require additional dating to solve this problem (Darienzo and others, 1994).

In contrast to Nestucca, the age of the second peat from Siletz is younger and does not overlap at  $2\sigma$  with the peats from Necanicum, Netarts, and Alsea. The young age is perhaps due to root contamination from above. The second buried peat at Ecola and Yaquina was not dated. The sands without accompanying subsidence stratigraphy that record the second event at the three northernmost estuaries

suggest deposition by a tsunami generated by an offshore subduction-zone earthquake off an adjacent segment of the Oregon coast to the south. The lack of evidence for this second event along the Washington coast further supports a segment rupture limited to the southern Oregon coast (Atwater, 1992). Possible segment boundaries are located either between the Netarts and Nestucca bays or between Siletz and Yaquina (Figure 1). Supporting a segment boundary between Netarts and Nestucca is the fact that there is evidence of subsidence for the second earthquake burial event at Nestucca but no such evidence at Netarts. Support for a segment boundary between Yaquina and Siletz includes evidence of subsidence at Yaquina, weak subsidence evidence at Siletz, and a possible segment boundary at this same location for the fifth earthquake burial event. Further work is necessary to accurately locate the boundary. Nevertheless, all estuaries were affected by this second paleoearthquake either directly, by subsidence and a tsunami, or indirectly, by a tsunami only. Therefore, the record of the second event could be considered synchronous among the estuaries on the northern Oregon coast.

The **third burial event** is recognized in all estuaries, and the ages of the buried peats at nearly all estuaries overlap at  $2\sigma$  (Alsea was not dated) (Figure 4). The exception is the age of the third buried peat at Nestucca, which overlaps all estuaries except Necanicum. A distinct sandy layer is present over the third buried peat at four of the seven northern estuaries but absent at Alsea, Siletz, and Netarts (Figure 2). The Hatfield site in the lower reaches of Yaquina Bay had tsunami sand deposited over what is considered the third buried peat, based on radiocarbon age (Figure 4). However, the third buried peat at other sites in Yaquina Bay is not capped by tsunami sands (Peterson and Priest, in preparation). The tsunami sand in the lower reaches of Yaquina Bay is not shown in Figure 2, because the representative stratigraphy for Yaquina in Figure 2 is from the upper reaches of the estuary (Darienzo and others, 1994). Based on ages, evidence of subsidence, and one-to-one correspondence of tsunami sand from the Hatfield site with subsidence, this third event possibly occurred synchronously from the Necanicum River to Alsea Bay.

The **fourth burial event** is recognized in all seven estuaries. At five of the estuaries, the ages of the event overlap at  $2\sigma$  (no age from Ecola or Nestucca). Tsunami sands overlie peats in four out of seven estuaries but are absent at core sites in Ecola and Nestucca. Based on ages, evidence of subsidence, and one-to-one correspondence of tsunamis with subsidence, this fourth event possibly occurred synchronously from the Necanicum River to Alsea Bay (Figures 2 and 4) (Darienzo and others, 1994; Peterson and Priest, in preparation).

The **fifth burial event** is recognized in all estuaries. Only three of the seven estuaries were observed to record tsunami sands above buried peats (Figure 2), and the age ranges for the fifth event overlap in only three out of the five estuaries dated (Figure 4). The ages of the event at Alsea and Yaquina, the two southernmost estuaries, are greater than at the other dated estuaries. This suggests a separate event (or more) for them and a segment boundary between Yaquina and Siletz. Or, buried peats with similar ages have not been identified in adjacent estuaries because of nondeposition or erosion. Ages of

the fifth buried peats at Ecola and Necanicum are needed to support synchronicity of the event northward from Netarts (Figure 1). However, Netarts, Ecola, and Necanicum show evidence for subsidence. If there is a segment boundary between Netarts and Ecola, one would expect tsunamis produced from earthquakes north and south of the boundary to deposit tsunami sand on nonsubsided marshes in estuaries of adjacent segments. If sands had been deposited, the stratigraphy would show these sands within the peat rather than on top of a peat that is buried by estuarine sediments. No evidence of a tsunami deposit from an adjacent earthquake was identified in the cores, which suggests synchronicity for the fifth event from Siletz to Necanicum, a distance of 123 km, rather than segmentation. The same arguments apply for southward extension of the event to Alsea Bay. This lack of tsunami sands unrelated to subsidence supports synchronicity of the fifth event between Alsea and Necanicum. However, tsunamis do not always leave a deposit. Therefore, the absence of a tsunami sand in horizons other than those immediately overlying a buried peat can not rule out segmentation. Nonetheless, tsunami sand layers not associated with buried peats have been recognized for the second event. In estuaries such as Netarts, where marshes are separated from the Pacific Ocean by a thin sand spit, the potential is high for sand deposition by a tsunami that was generated by an adjacent segment rupture. Only one tsunami deposit of this type was found in the proximal marshes of Netarts. Therefore, this implies no segmentation on the northern Oregon coast for five out of the six events.

The **sixth burial event** is recognized in all estuaries, with tsunami sands overlying peats in three estuaries (including two sites at Netarts not depicted in Figure 2). The ages overlap, with the exception of Necanicum, which supports synchronicity of the event from Alsea to Ecola. Extension to Necanicum is still possible, given that the distance from Ecola to the Necanicum is only 14 km. At Necanicum, there is evidence for subsidence but no evidence of tsunami sand not connected with subsidence, that is, there is no sand directly overlying a buried peat. This suggests synchronicity of the event between Alsea and Necanicum and no segment boundary between Ecola and Necanicum.

In summary, synchronicity between Alsea and Necanicum is supported for all events, except events number two and possibly number five, based on the one-to-one correspondence of tsunami sands and earthquake-buried peats. Event two is also synchronous between Alsea and Necanicum but does not show subsidence in at least three of the seven estuaries. A segment boundary for the second earthquake possibly exists between either Siletz and Yaquina or between Netarts and Nestucca. Based on radiocarbon ages only, there is the possibility of a segment boundary between Yaquina and Siletz for event five.

Synchronicity of events could possibly extend far to the north and south of the seven estuaries discussed here. Based on radiocarbon ages and similar peat development, the last three events recorded in Grays Harbor and Willapa Bay, Washington, are comparable to the first, third, and fourth events of this study (Atwater, 1987, 1992). Extension of event synchronicity to Grays Harbor would add approximately 110 km to the northern rupture length (Figure 1). Synchronicity could also be tentatively extended south to southern Oregon and northern California. For example, South Slough in southern Oregon contains six buried peats within 3 m of the surface from the last 2,800 years (Figures 1 and 2) (Peterson and Darienzo, 1989; Nelson, 1992a). This extension would add 100 km to the rupture length. Clarke and Carver (1992) document four or five probable coseismic subsidence events in the Mad River Slough of Humboldt Bay in the last 1,423 to 1,690 years (Figure 1). The ages and the number of events resemble the data from northern Oregon. This would add approximately another 275 km (distance from South Slough to Humboldt Bay) to the rupture length. However, further work in the estuaries between Alsea and Humboldt is needed to test this southward-extension hypothesis.

## Paleomagnitudes

Coseismic subsidence from subduction-zone earthquakes probably occurred synchronously among seven estuaries at least four and possibly five times in the past 3,000 years along the northern Oregon coast. Magnitudes were based on a rupture length of 175 km (distance between Alsea Bay and Necanicum), a rupture width of 60 km, a convergence rate of 4 cm/yr, and an average recurrence interval of 400 years.

We calculated paleomagnitudes with two different equations, (1) the magnitude equation of Abe, which is based on ruptured area only, and (2) the moment magnitude ( $M_W$ ) equation, which combines rupture area, convergence rate, and recurrence interval.

According to the magnitude equation of Abe, the magnitude of the Holocene earthquakes for the first event and the third to sixth events would be 8.0. With a range of lengths (105–175 km) and widths (60–90 km) on the northern Oregon coast, the magnitudes would be between 7.8 and 8.2. If extended to Grays Harbor, Washington (rupture length of 285 km), the events one, three, and four would yield magnitudes between 8.2 and 8.4.

According to the moment magnitude equation, the magnitudes of paleoearthquakes one and three to six between Alsea and Necanicum (rupture length of 175 km) would be  $M_W$  8.4, based on a rupture width of 60 km (Figure 1). If the length was shortened to 105 km (the distance from Netarts to Alsea), the magnitude would be  $M_W$  8.2. Extending events one, three, and four to Grays Harbor, Washington, would yield a magnitude of  $M_W$  8.6. With a range of convergence rates of 3.5–4.5 cm/yr (Nishimura and others, 1984), average recurrence intervals of 200–600 yrs (Darienzo and Peterson, 1994), rupture lengths of 105–285 km, and rupture widths of 60–90 km, the range of magnitudes for paleoearthquakes between Alsea and Necanicum would be  $M_W$  8.1–8.8 and between Alsea and Grays Harbor  $M_W$  8.4–8.9.

## Average recurrence intervals

Each estuary records six earthquake events within the last ~3,000 years. Representative stratigraphy and associated radiocarbon ages are shown in Figure 2. From ages and numbers of earthquakes, the range of average recurrence intervals is calculated for each estuary, using both five and six events (Table 2). The average recurrence interval for each estuary falls between 200 and 600 years (to the nearest 50 years). One exception is in averaging the last five events at Yaquina Bay, which increased the upper value in the range to 650 years. The average recurrence intervals, calculated from calibrated ranges of ages generated by a computer program, are not significantly different from the average recurrence intervals calculated by the method in this paper. The average interval range (350–700 years) for South Slough, a southern Oregon estuary included for comparison, is relatively consistent with these results (Figures 1 and 2; Tables 1 and 2) (Peterson and Darienzo, 1989). The next-to-youngest event (burial event two) at Netarts and Ecola does not represent an earthquake with associated subsidence, rather a tsunami deposit from an earthquake produced in an adjacent segment (Darienzo, 1991; Galloway and others, 1992). However, this event was included in recurrence interval calculations, because a tsunami from an adjacent segment will be very destructive along the coast, even in the unsubsided segment. Therefore, the second event at Netarts and Ecola shows evidence for earthquakes and should not be removed from the recurrence interval calculations.

## CONCLUSION

Evidence for great Holocene subduction-zone earthquakes is documented in individual estuaries along the northern Oregon coast. Stratigraphic evidence, such as number of events in the top 3 m, depth of buried peats, presence of distinct tsunami layers, and radiocarbon ages, is similar among seven estuaries. This similarity suggests synchronicity of earthquake-induced subsidence along the

Table 2. *Ranges of average recurrence intervals of estuary burial events*

No. of intervals averaged	Nec*	Eco*	Net*	Nes	Sil	Yaq	Als	SS
4			250-490 (230-510)	240-500 (210-530)	230-490 (200-480) 210-470 (190-450)	380-640 (400-650)	290-570 (290-600)	340-640 (330-700) 410-680 (370-700)
5	200-410 (190-410)	350-550 (350-610)	340-550 (350-600)	330-540 (340-580)	340-570 (340-590)	330-560 (360-590)	330-520 (340-530)	360-590 (370-660) 420-620 (400-660)

\* The second event, which contains evidence for a tsunami but no evidence of subsidence (except perhaps at Necanicum), is included in range calculations.

Ranges in parentheses are based on calibrated ages from Table 1. The two sets of values for Siletz in the four-interval row include Salishan (upper set) and Millport; the two sets of values for South Slough in both four- and five-interval rows represent calculations based on Winchester and Day Creeks (upper set in each row) and Day Creek only.

Nec = Necanicum, Eco = Ecola, Net = Netarts, Nes = Nestucca, Sil = Siletz, Yaq = Yaquina, Als = Alsea, and SS = South Slough.

northern Oregon coast. Synchronicity of events from Alsea Bay to the Necanicum River, covering a distance of 175 km, is best documented for the first, third, and fourth and reasonably documented for the fifth and sixth events. The second event may be synchronous from Alsea to Necanicum, based on the presence of tsunami sands, even though evidence of earthquake-induced subsidence for this event is absent in at least the three northernmost estuaries.

The magnitudes of the Holocene earthquakes recorded along the northern Oregon coast are probably at least 8.0, based on a rupture length of 175 km, a minimum rupture width of 60 km, a recurrence interval of 400 years, and a convergence rate of 4 cm/yr. If the magnitudes are calculated with a range of convergence rates, average recurrence intervals, rupture lengths, and rupture widths, the magnitudes are no less than 7.8 and possibly as large as 8.8. The average recurrence interval for earthquakes recorded in each estuary ranges from 200 to 600 years.

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## DOGAMI PUBLICATIONS

Released November 9, 1994

***Geologic Map of the Tenmile Quadrangle, Douglas County, Oregon***, was published in the DOGAMI Geological Map Series as map GMS-86 (price \$6). The Tenmile quadrangle includes Tenmile Valley and a major portion of Olalla Creek to the south. The quadrangle is at the southeast corner of a block of eight quadrangles for which geologic maps have been already produced by DOGAMI or are in progress. The quadrangle maps published so far are Camas Valley, Kenyon Mountain, Mount Gurney, Remote, Reston, and the new release Tenmile.

The new, two-color geologic map and cross section were produced by Thomas J. Wiley and Gerald L. Black of DOGAMI. At a scale of 1:24,000 (1 inch = 2,000 feet), it depicts the geology in greater detail than any previous map, identifying 16 rock units and showing faults and landslides. A five-page text discussing rock units, structural geology, and geologic history accompanies the map sheet.

The Tenmile quadrangle is underlain by complex geology that includes rocks ranging in age from Jurassic (about 200–140 million years ago) to early Eocene (about 50–40 million years ago).

Released December 20, 1994

***Oregon's Mineral Industries: An Assessment of the Size and Economic Importance of Mineral Extraction in 1993***, Open-File Report O-94-31 (price \$6). According to the study, in 1993 the value of minerals produced in Oregon totaled \$239.9 million. This value was measured at the point of production and does not include shipping and special processing costs. If these were added in, the total value would nearly double. Oregon's mineral industries directly supported 2,039 full-time jobs in the state. In addition, over 3,000 other workers were employed in related activities such as trucking and the manufacturing of concrete products.

Written by DOGAMI minerals economist Robert Whelan, the report is the most complete measurement of the State's mineral industry ever made. Whelan sent survey questionnaires to 878 mineral producers in Oregon and received a response from 84 percent. According to Whelan, "This survey represents the first comprehensive accounting of Oregon's mineral output ever done. Now, questions about the size and economic importance of mineral production in Oregon can be answered with real data."

Construction aggregates, such as crushed rock and sand, accounted for 89 percent of Oregon's mineral production. Ranking second in value was natural gas. Most of the remaining production was attributed to industrial minerals, the most important of which were limestone, pumice, and diatomite. Gemstones valued at over \$1.3 million were mined. Gold production, all of which came from small seasonal operators, totaled \$778,000.

The survey indicates that Oregon consumed 51.2 million tons of construction aggregate in 1993. This figure is much higher than previously thought.

Released December 29, 1994

***Geologic Map of the Damascus Quadrangle, Clackamas and Multnomah Counties, Oregon***, by Ian P. Madin, has been published in the DOGAMI Geological Map Series as map GMS-60 (price \$8). The full-color geologic map identifies 28 different bedrock and surficial rock units and many previously unrecognized faults and is accompanied by three geologic cross sections. A separate sheet provides geochemical data for over 80 samples taken in the quadrangle. A nine-page text contains rock-unit explanations, discussions of structure and geologic history, an aeromagnetic map of the quadrangle, and location maps for geochemical samples and the many water wells used to interpret the structure of the area.

The main portion of the map area lies between the Clackamas River and Johnson Creek. It has been shaped by basalt, first in gigantic flows from eastern Oregon and later in faulting-related eruptions, and by extensive accumulations of sediments from the Columbia River, the once-glaciated Cascade Mountains, and the catastrophic floods that inundated the area during the late ice age.

Flood-deposited agricultural soil, sand, gravel, stone, and clay attracted people to this area. Large deposits of basalt and aggregate remain throughout the quadrangle, but their use faces competition from other land uses. The varied geology provides unique recreation opportunities for rock climbing as well as river running. The topography, born of faulting and volcanic eruptions, offers striking scenery that attracts increasing interest by housing developers. The complex deformation of the area complicates the understanding and managing of ground-water resources, while residences and a growing nursery industry are placing increasing demand on ground water.

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# Oregon's mineral industries—An assessment of the size and economic importance of mineral extraction in 1993

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*This report was recently released by the Oregon Department of Geology and Mineral Industries as Open-File Report O-94-31. It is reprinted here in an abbreviated and slightly updated form.* —ed.

## INTRODUCTION

The Oregon Department of Geology and Mineral Industries has completed the most comprehensive survey of mineral production ever done in Oregon. The total value of products extracted from Oregon's mineral properties in 1993 was \$239.9 million. The industry contributed \$102.4 million to the State's economy in the forms of wages, profits and taxes.

The survey counted output from mines, quarries, sand and gravel pits, river dredges, gemstone deposits, public lands, and natural gas wells.

Production was measured at its point of removal—that is, before any processing by which physical properties, other than particle size and cleanliness, were changed. So-called downstream products, such as cement or cut gemstones, were not counted.

Our production data differ from figures reported by the U.S. Bureau of Mines (USBM) in its annual *Mineral Industry Surveys*. This is largely the result of differences in the types of mineral products covered in the surveys. The USBM data for Oregon include many downstream products, but they exclude natural gas. Our survey measures only raw mineral output, and it includes natural gas.

We received replies from 84 percent of the 878 surveys that were mailed. We estimated the values of nonrespondents using combinations of site visits, public data, and third-party information. Estimates were also made for informal miners. These include farmers, ranchers, loggers, gemstone collectors, and other small producers.

## MINERAL PRODUCTION IN OREGON IN 1993

Total mineral production value in Oregon during 1993 was \$239.9 million. Sand, crushed stone, gravel, and other construction aggregates accounted for 89 percent of the total. Ranking second was natural gas. Industrial minerals, such as clay, limestone, and pumice, accounted for most of the rest. These totals are shown on Table 1.

Half of all the active private mining businesses in 1993 had no more than one full-time worker. A small operation is an advantage in mining. Single-person operators can often opt out of workers' compensation coverage. That insurance is expensive, costing a minimum of \$9.89 for every \$100 paid to mine workers.

Oregon was the only western U.S. state, other than Hawaii, with no major working metal mines in 1993. Oregon did produce 2,021 troy ounces of gold, but all of it came from recreational and small seasonal mining operations. No gold mine provided year-round employment in 1993.

**Crushed rock and shale** production totaled 23.9 million tons and was valued at \$115.5 million. The average selling price was \$4.83 a ton. Prices varied greatly, however, depending on local conditions. Prices tended to be higher in the Portland and Bend markets, where construction activity was strong.

Crushed rock is used in roads and buildings. A familiar crushed rock product is asphalt pavement used in many parking lots and roads. Rock is mined in quarries and then fed into special rock crushing equipment. After crushing, it is cleaned, sorted by size, and stored for eventual blending to customer specifications.

Most crushed rock quarries in Oregon are idle except when local

Table 1. 1993 Oregon mineral production (in short tons, unless otherwise noted)

Product	Quantity	Dollar value
Crushed rock and shale	23,888,974	\$115,456,068
Pit run rock	2,103,315	3,418,975
Decomposed granite	362,763	Combined <sup>1</sup> 2,346,856
Cinders	299,689	
Sand and gravel from waterways	3,096,980	Combined <sup>1</sup> 90,895,172
Sand and gravel from pits	17,732,489	
Fill material	1,255,907	1,890,705
Common clays and bentonite	300,018	2,070,792
Other industrial minerals <sup>2</sup>	N/A	14,625,877
Gold (in troy ounces)	2,021	788,000
Gemstones	N/A <sup>3</sup>	1,336,743
Natural gas (thousand cu.ft)	3,534,243	7,072,554
<b>STATE TOTAL</b>		<b>\$239,901,742</b>

<sup>1</sup> Values were combined so that individual producer data can be kept confidential.

<sup>2</sup> Other industrial minerals are agricultural and industrial limestone, dolomite, diatomite, perlite, zeolites, emery, dimension stone, building stone, decorative stone, industrial silica sand, and soapstone.

<sup>3</sup> Not available.

construction activity picks up. Then, portable rock-crushing equipment is brought in and operated as needed. Other quarries, especially in large markets, have permanent rock-crushing equipment nearby, which runs regularly.

The term "shale" is used in Oregon for both actual shale and some types of layered volcanic rock that break apart easily. This characteristic makes production of shale less expensive than production of the more common types of crushed rock. In Oregon, volcanic shale is used as a substitute for crushed rock, which is why we include it here. Most of it is mined in southwestern Oregon.

The production of **pit run rock** totaled 2.1 million tons and was worth \$3.4 million in 1993. Pit run rock is rock that is quarried but not crushed. At an average price of \$1.63, it is a low-value product. Pit run rock is used in construction where bulk, rather than product consistency, is important. Logging companies are also big consumers. Pit run rock makes rough, yet inexpensive logging roads that are adequate for log trucks. The USDA Forest Service, on the other hand, uses only crushed rock because it wants smooth roads that are accessible to smaller vehicles operated by recreational visitors.

Production of **decomposed granite** in the state totaled 362,763 tons. Decomposed granite is an unusual aggregate material found in Jackson County and surrounding areas. It is a deeply weathered granite. It compacts so readily that it is used in local construction for high-quality fill. One common use for fill is preparing and leveling ground for new buildings.

**Cinder** is a lightweight volcanic rock. It is usually reddish colored. In 1993, a total of 299,689 tons of cinder was mined. Cinder

is crushed into small gravel that is used for sanding icy roads. Commercial landscapers use larger cinder gravel as a type of mulching stone. In central Oregon, where most of the cinder is mined, it is used for road pavement. Because it is so easily crushed, cinder gravel is considered a low-cost but inferior alternative to crushed rock.

**Sand and gravel** production totaled 20.8 million tons and was worth \$90.8 million. Just under 3.1 million tons of the sand and gravel produced in Oregon came from waterways such as the Columbia and Willamette Rivers. The average mine price from all sources was \$4.36 a ton.

Sand and gravel are mined from pits or are extracted from waterways by dredges. The material is then cleaned, sorted by size, stored, and later blended to customers' orders. Some producers will crush any large pieces they extract. This way, they can better match the demands of the local market for different particle sizes.

Unlike sand and gravel that are manufactured from crushing rock, natural sand and gravel tend to have particles with rounded edges and hard surfaces. This makes them ideal for concrete. Particle roundness allows the concrete to flow better when it is poured. Hard surfaces keep the particles from absorbing expensive cement.

Concrete is a mixture of cement, aggregate, and a few other ingredients. Cement is expensive. When you make concrete, it is worth while to mix in as little cement as possible. Using rounded sand and gravel, especially material mined from rivers, lets you economize on the amount of cement you have to add. Natural sand and gravel also usually make a concrete of better quality.

**Fill**, as defined in our survey, is unprocessed loose material that is sold for low-value applications such as road embankments and leveling-off land at construction sites. Soil and unprocessed sand are two common forms of fill. At some rock crushing plants, they sell very fine rock particles as fill. In 1993, 1.3 million tons of fill worth \$1.9 million were produced in Oregon. The average price was \$1.51 per ton. Prices varied from a few cents to over \$2 a ton.

**Natural gas** production totaled 3,534,243 thousand cubic feet (MCF) and was worth \$7.1 million. All of it was produced from the Mist Gas Field in Columbia County. Besides contributing to local employment, the County earned royalties from the wells and used the money to help fund its public schools.

The Northwest Natural Gas Company sells the production from the Mist field to its customers in Oregon. The company also uses the field to store gas bought from producers in other places when prices are low. Then it takes the gas out of storage during cold periods when demand rises and out-of-state gas prices become prohibitively high. Doing this helps save money and assures the state that it will have enough gas on hand for emergencies.

Oregon produced 300,018 tons of **common clays and bentonite** in 1993, with a value of \$2.1 million. Most of the common clays were made into bricks. Bentonite, which is a special class of clay, went into engineering projects such as ponds and waste-disposal sites.

Collectively, \$14.6 million worth of other industrial minerals was mined in Oregon. Industrial minerals are mined products that are not made into metals or used as common construction aggregate. The individual quantities and values cannot be shown because there are too few producers of each of them in Oregon. We can say, however, that over 90 percent of the production is attributable to three industrial minerals. They are diatomite, limestone, and pumice.

**Diatomite** is mined in Lake, Harney, and Malheur Counties. It is a rock that is formed from the skeletons of single-celled algae. Diatomite is used for filters in water purification and as an absorbent material. One well-known diatomite product is cat litter.

Most of the state's **limestone** is mined in Baker County. It is made into cement and agricultural lime. Some of it is also used in local beet sugar refineries.

**Pumice** is an air-filled volcanic rock common to central Oregon. Pumice is used in construction, landscaping, and horticulture, for stone-washing clothes, and as an additive for lightweight concrete.

Oregon produced several other industrial minerals in 1993. **Silica sand**, which is a quartz-rich sand, was mined in two places in the state. Most of it is used for making glass bottles. **Dimension and decorative stone** were produced in small amounts throughout Oregon and are used for landscaping and construction of buildings and walkways. **Zeolites** were mined in eastern Oregon. They are an unusual class of minerals used in certain chemical and industrial applications for their selective absorption properties. **Soapstone** was mined in southwestern Oregon. Soapstone is soft, attractive, and easy to carve. It is used by artists as a sculptural stone. **Perlite** was mined in eastern Oregon. Perlite is an unusual rock that puffs up when heated. You will find it in potting soils sold at most gardening shops. **Emery** was mined in Linn County. It is used for skid-resistant surfaces on sidewalks and bridges.

**Gold** production in 1993 totaled 2,021 troy ounces valued at \$788,000. These are rough estimates based on surveys of producers, geologists, gold buyers, and various field experts. Most of Oregon's gold came from Baker and Grant Counties. All of Oregon's gold came from small seasonal operations. They physically extract gold from soil and gravel. Only a handful of gold producers mined more than 10 oz of gold in 1993.

**Gemstone** mining totaled \$1.3 million. That makes Oregon the seventh largest producer in the United States. The output of gemstones is expected to more than triple in 1994 because of expanding markets for sunstones and opals. Those two gemstones accounted for 65 percent of Oregon's output in 1993.

Sunstones are clear feldspar crystals. They are found in Harney and Lake Counties. Sunstones come in a wide range of colors. They sometimes contain minuscule flecks of natural copper metal. The most valuable sunstones are red with copper flecks. Most Oregon sunstones are sent to Asia for faceting. The cut stones are then sold to jewelry makers around the world.

Oregon produces precious fire and blue opals. Most of the production comes from Morrow and Lake Counties. Small amounts are found elsewhere in the state.

Other gemstones mined in Oregon include agates, geodes, picture rock, jasper, obsidian, thunder eggs, and quartz crystals. Most of these are collected by individuals and are not extracted from regular mines.

## REGIONAL ECONOMIC IMPACTS

In 1993, mineral production added \$102.4 million in taxes and income to Oregon's economy. This came in the forms of payroll, employee benefits, operating profits, taxes, royalties, and fees. Worker payrolls and benefits accounted for 57 percent of the total. The industry had the equivalent of 2,039 full-time employees engaged in mineral extraction. In addition, it employed many workers for related activities such as trucking, operating asphalt plants, and marketing.

Economic impact is an appraisal of the increased sales or income in an economy due to an activity. It is an estimate of the benefits and costs. In this analysis, we measure the economic impact by estimating the value added by Oregon's mineral industries. It is the sum of wages, profits, rents, royalties, and indirect business taxes.

In our analysis, we used industry averages, contacts with producers, state payroll data, and proprietary consolidated financial statements. With this information and our own survey we were able to estimate economic impacts.

Employment is a key variable. Most mines are seasonal. A mine with six workers may run, for instance, for two months. That equals 12 months of work in total or the equivalent of one full-time employee. For this analysis, we converted all part-time and seasonal labor into the equivalent of full-time employees working for a whole year.

Our survey revealed that while 2,938 people worked at Oregon's mines and natural gas field in 1993, the total amount of work done equaled 2,039 full-time workers.

Our estimate of mining and natural gas employment is 56 percent higher than the figure reported by the Oregon Employment Division. One reason for the difference is that the state collects data only on workers covered by unemployment insurance. Several hundred mining proprietorships and partnerships are not covered. The state agency also does not count all the county road and forestry workers, who engage in mining. They are classified as public workers rather than miners.

Unlike the Employment Division, we counted all the mine and natural-gas well employees, including part-time workers. The difference in coverage between our survey and the Division's is substantial. The number of mines reporting to the Employment Division in 1993 was about 100. Over 600 establishments reported workers to our survey.

Mining occurs in every county in Oregon, but most of it is concentrated along the Interstate 5 corridor. The highest dollar value of mineral production in 1993 occurred in the Portland metropolitan area. Washington County led the state in the value of minerals produced.

Statewide, besides the \$102.4 million directly added to the economy, the mineral industry created indirect benefits. These result from the money spent in local communities that, in turn, creates more employment and spending.

One of the most important indirect impacts is found in transportation. From the survey, we estimate that 973 workers (mostly truck drivers) were used to ship Oregon's mineral products. Another large indirect impact is the work created at asphalt and concrete plants. These businesses depend on construction aggregates and employed 2,071 workers in 1993.

We cannot calculate total indirect benefits because of limitations on economic data. However, it is clear that local mining creates downstream jobs in shipping, concrete products, and many other areas.

Another way to view the economic impact is to consider what Oregon would be like if no mineral extraction occurred. The state would have to import all its minerals. Immediately, 2,039 direct jobs would be lost, as would \$102.4 million in taxes and income. The indirect losses would also be great as customers would have to pay more for minerals imported from out-of-state.

Table 2 shows the direct economic impact of mining around Oregon. The state is divided into 11 groups of counties (Figure 1). This was done to ensure the anonymity of survey respondents.

## HOW MINERALS WERE SHIPPED IN 1993

Our survey asked producers about shipping. This was done because transportation is the biggest cost in marketing some minerals. Often mineral deposits can only be economically developed if they are close to shipping routes or consumers.

By far, trucking is the principal way minerals are shipped. Almost half of the state's output goes on trucks owned by mine operators. Another 41 percent is loaded on trucks owned by customers and independent haulers.

Water transportation, which is mainly by river barge, had a 5.8-percent share of the mineral market in 1993. Railroads carried only 3.3 percent. Another 3.0 percent was shipped by other means or not shipped at all. Most of this was natural gas being transported by pipelines from Columbia County.

Table 3 is a summary of how Oregon's mineral production was shipped in 1993. The shares and amounts are based on dollar values.

Table 4 is a compilation of how construction aggregates were shipped from production sites. Unlike the previous table, amounts and percentages on Table 4 are based on tons of aggregates shipped.

Table 2. *Regional economic impacts of 1993 mineral production in Oregon*

Region (counties)	Employment <sup>1</sup>	Value of production	Economic impact
<b>Central</b> (Crook, Deschutes, Jefferson, Wheeler)	188	\$20,061,110	\$10,325,911
<b>Inland southwest</b> (Douglas, Jackson, Josephine)	228	21,312,023	9,894,261
<b>North-central</b> (Hood River, Gilliam, Morrow, Sherman, Wasco)	51	4,673,430	2,089,123
<b>North coast</b> (Clatsop, Lincoln, Tillamook)	115	9,724,597	4,620,201
<b>Northeast</b> (Baker, Grant, Umatilla, Union, Wallowa)	198	20,043,523	8,730,037
<b>North Willamette Valley</b> (Marion, Polk, Yamhill)	199	28,713,306	11,500,240
<b>Portland Area</b> (Clackamas, Columbia, Multnomah, Washington)	451	76,806,862	26,967,950
<b>South-central</b> (Lake, Klamath)	125	9,549,764	5,187,960
<b>South coast</b> (Coos, Curry)	115	7,541,531	4,216,523
<b>Southeast</b> (Harney, Malheur)	101	11,599,750	5,376,862
<b>South Willamette Valley</b> (Benton, Lane, Linn)	270	29,875,845	13,505,071
<b>STATE TOTAL</b>	<b>2,039</b>	<b>\$239,901,741</b>	<b>\$102,414,141</b>

<sup>1</sup> The equivalent number of full-time, year-round jobs directly in mining and mine supervision.

Table 3. *How Oregon's minerals were shipped in 1993*

Mode of transportation	Value of minerals	Percent of total
Truck owned by producer	\$113,635,658	47.4
Truck owned by other entity	97,265,499	40.5
Railroad	7,983,062	3.3
Water	13,928,842	5.8
Other <sup>1</sup>	7,088,680	3.0
<b>TOTAL</b>	<b>\$239,901,741</b>	<b>100.0</b>

<sup>1</sup> Shipment by natural-gas pipeline, U.S. mail, air freight, and delivery services. Also includes minerals used at production site.

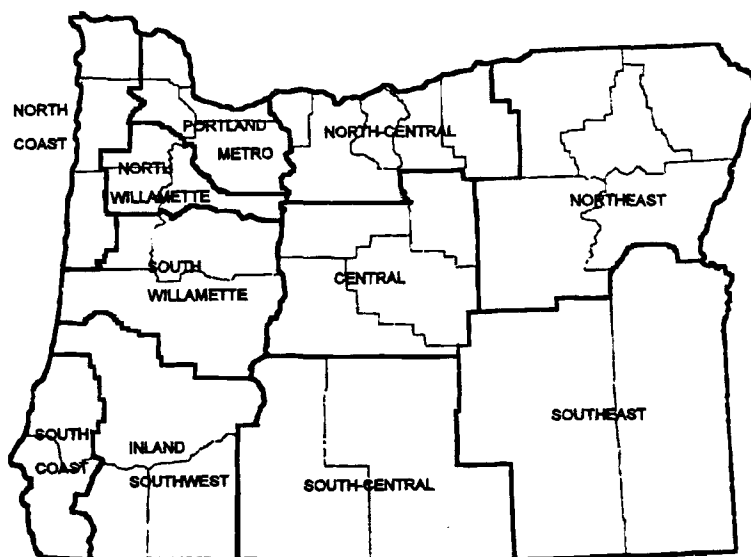


Figure 1. *Regions of the state as used in Tables 2 and 5.*



In 1993, 92.1 percent of Oregon's aggregate production was shipped by truck. Nearly 44.9 million tons went on trucks. If the average load was 20 tons, that would amount to 2,244,843 individual truck shipments. This has a direct effect on road congestion and pavement damage. In addition to shipments from Oregon mines, much of the aggregate coming into the state from Washington was trucked in. These shipments are not counted in Table 4.

Most aggregate is trucked less than 15 miles. Shipping distances have been growing, however, because mines that are close to markets are being replaced by mines farther away. Consumers are compromising by using a combination of lower quality aggregate and shipping-in material from more distant mines. This directly increases the cost of road and building construction for communities.

Table 4. How aggregate was shipped in 1993

Mode of transportation	Tons	Percent of total	Est. number of loads <sup>1</sup>
Truck owned by producer	25,212,424	51.7	1,260,621
Truck owned by other entity	19,684,435	40.4	984,222
Subtotal for all trucks	44,896,859	92.1	2,244,843
Railroad	1,029,265	2.1	10,293
Water	2,817,13 <sup>a</sup>	5.8	1,875
Other <sup>2</sup>	860	0.0	0
TOTAL	48,740,117	100.0	2,257,011

<sup>1</sup> This assumes that the average truck carried 20 tons of aggregate, the average rail car carried 100 tons, and the average barge took 1,500 tons. The number of loads equals the number of one-way shipments.

<sup>2</sup> Aggregate that was mined and used on-site.

## CONSUMPTION OF AGGREGATES

In Oregon, construction aggregates are usually used within a few miles from where they are produced. We do know, however, that aggregate crosses state lines. Some of it comes in by rail from long distances.

In an informal survey, we estimated the amount of construction aggregate that moved between regions in our state. This gave us apparent consumption figures for 11 regions in the state (Table 5).

Apparent consumption equals production plus imports and minus exports. Actual consumption can differ from this because of inventory fluctuations. For construction aggregates, however, such variations are rarely significant.

The biggest flow of aggregates across regional borders happens in the Portland area. That region imports, on a net basis, about 3.3 million tons of aggregate from Clark County in Washington and from Oregon counties to the south. Most of the aggregate from Washington State is trucked down Interstate 205 to Clackamas County.

Eastern Oregon exports sizable amounts of sand and gravel to Washington and Idaho. Southern Oregon exports a small amount to California. Railroads also ship aggregate across state lines. These shipments are mostly crushed rock that the railroads use themselves.

Aggregate consumption in Oregon totaled 51.2 million tons in 1993. That equals 16.8 tons per capita. The intensity of use ranged widely from area to area. It was generally greater in rural counties with low population densities. Consumption in southeastern Oregon, which includes Harney and Malheur Counties, was 34.1 tons per capita. In urban areas, it was much less. In the Portland metropolitan area, the per capita consumption totaled 12.7 tons.

## SUPPLY OF AGGREGATES

In addition to the aggregate produced by privately owned mines, large quantities are mined by or for public agencies. Significant amounts are also produced by forest products companies and Indian Reservations. This is an important part of the state's aggregate supply.

In 1993, a total of 902,080 tons of aggregate was mined from BLM, USFS, and State Forest land. This does not include private, county, and State Highway Division mine production on those lands.

Table 5. 1993 apparent consumption of aggregates (in tons) for 11 regions in Oregon<sup>1</sup>. Regions and county allocation same as in Table 2 and Figure 1

Region	Local production	Net imports (exports)	Apparent consumption	Per capita consumption <sup>2</sup>
Central	3,808,519	62,000	3,870,519	32.7
Inland southwest	5,470,082	(30,000)	5,440,082	17.0
North-central	973,788	56,000	1,029,788	19.6
North coast	2,213,547	55,000	2,268,547	23.5
Northeast	3,446,588	(317,100)	3,129,488	26.4
North Willamette Valley	6,607,330	(613,500)	5,993,830	16.2
Portland area	13,346,057	3,292,500	16,638,557	12.7
South-central	2,098,955	0	2,098,955	31.0
South coast	1,688,712	40,000	1,728,712	20.6
Southeast	1,273,312	(100,000)	1,173,312	34.1
South Willamette Valley	7,813,227	(12,000)	7,801,227	16.7
STATE TOTAL	48,740,117	2,432,900	51,173,017	16.8

<sup>1</sup> Includes crushed rock, pit run rock, sand and gravel from all sources, cinder, fill, and decomposed granite.

<sup>2</sup> Apparent consumption divided by mid-1993 population.

The Oregon Department of Transportation (ODOT) produced 2,011,120 tons in 1993. ODOT uses its own aggregate whenever commercial supplies are impractical. This tends to happen in eastern and central Oregon. That is where over 92 percent of ODOT's mining took place.

County road departments are major aggregate producers. Some counties also have forestry departments that occasionally run mines. A few cities and local governments have mines or river dredging operations. All of these counties and local agencies mined 1,952,723 tons of aggregate in 1993.

Table 6 is a list of these producers broken down by major regions.

Forest products companies need rock for their roads. Even if they are not logging, companies will put rock on roads that they use for forest management, fire prevention, and thinning.

Their need is greatest on main hauling roads that cross rough terrain in rainy areas. The need for aggregate by the timber industry is, therefore, greatest in the Coast Range. It is particularly high in the central Coast Range where the poor-quality local rock is soft and weathers quickly. It must be replaced often. As you move further east, the amount of aggregate needed for every mile of road declines. In parts of eastern Oregon, some logging roads use no mined aggregate at all.

Table 6. 1993 aggregate mining by public agencies (in tons)

Region	BLM, USFS, State Forests <sup>1</sup>	ODOT	Counties and local governments
Eastern Oregon <sup>2</sup>	308,188	1,031,900	648,730
Central Oregon <sup>3</sup>	101,631	853,605	835,320
Western Oregon <sup>4</sup>	492,261	125,615	468,637
STATE TOTAL	902,080	2,011,120	1,952,687

<sup>1</sup> Excludes production captured elsewhere in the survey from ODOT, county road departments, local governments, and commercial mines operating on BLM and USFS lands.

<sup>2</sup> Baker, Grant, Harney, Malheur, Umatilla, Union, and Wallowa Counties.

<sup>3</sup> Crook, Deschutes, Gilliam, Hood River, Jefferson, Klamath, Lake, Morrow, Sherman, Wasco, and Wheeler Counties.

<sup>4</sup> Clatsop, Columbia, Clackamas, Multnomah, Tillamook, Washington, Yamhill, Marion, Polk, Lincoln, Linn, Benton, Lane, Douglas, Coos, Curry, Jackson, and Josephine Counties.

Because forests are usually far from commercial mines and quarries, timber companies often mine their own aggregates. As long as the company does not sell the aggregate, it can mine without filing mining permits. It still must abide by forestry practices and regulations. Production of this type totaled 2,283,843 tons in 1993. The industry probably bought an additional 1,344,000 tons of aggregate from commercial mines.

Much of the aggregate produced on USFS and BLM land is used for logging roads. Together, these agencies' use in forestry is about 600,000 tons. Oregon's Forestry Department uses all its aggregate for logging roads. In 1993, the agency mined 243,538 tons. Indian Reservations mined 107,200 tons for their logging roads.

We estimate that, in total, the timber industry consumed 3,984,581 tons of aggregate in 1993. Of that total, 1,209,349 tons were approximated statistically and not directly surveyed. This was based on information from forest products companies, regulators, and consultants. We also relied on forest ownership and harvest data.

Indian Reservations mined a total of 176,276 tons of aggregate in 1993. The Warm Springs and Umatilla Reservations produced nearly all the aggregate from Reservations in Oregon.

### MINING ON USFS AND BLM LANDS

USDA Forest Service lands are an important source of minerals. We believe that, in 1993, the true market value of minerals mined on USFS lands was \$3.5 million. This does not include mining by ODOT, county road departments, and a few commercial operators. Much of the net production of aggregates is used for maintaining and building roads on USFS land. Production for roads is down sharply from previous years because of budget constraints.

USFS lands were the main source of gold mined in Oregon. A small amount of decorative stone and perlite were also taken from USFS lands. This production is summarized in Table 7.

Table 7. 1993 mining on USDA Forest Service lands (in tons, unless otherwise noted)

Commodity	Production
<b>Net production of aggregates<sup>1</sup></b>	
Crushed rock	562,898
Pit run rock	33,792
Sand, gravel, and fill	30,997
Cinders	16,027
All aggregates (net)	643,714
Estimated production by counties, ODOT, and private mines counted elsewhere	315,000
Gross production of aggregates	958,714
<b>Other minerals</b>	
Decorative stone	2,096
Perlite	50
Gold (in troy ounces)	1,657

<sup>1</sup> Net production includes output for USDA Forest Service internal use on its roads, mining done by small producers, material taken from community pits, material removed by individuals with free-use permits, and production tied to timber sales. Production by ODOT, county road departments, local governments, and some commercial mining companies is not included in net production. These amounts are reported elsewhere in the survey.

Production on BLM lands in 1993 was well below the levels of past years. The estimated market value of net mineral production totaled only \$272,887. The BLM used to be a major aggregate producer, but output has been sharply curtailed due to budget cuts and falling timber harvest revenues.

The agency uses money from timber sales to pay for the crushed rock it produces for its own roads. The BLM, for several years now, has relied on old stockpiles of crushed rock and has supplemented it with small purchases from commercial sources.

Table 8 is a summary of BLM mineral production for 1993.

Table 8. 1993 mining on Bureau of Land Management properties (in tons, unless otherwise noted)

Commodity	Production
<b>Net production of aggregates<sup>1</sup></b>	
Crushed rock	17,593
Pit run rock	5,238
Sand and gravel	2,221
Fill	3,060
Cinders	26,716
All aggregates (net)	54,828
Estimated production by counties, ODOT, and private mines counted elsewhere	259,880
Gross production of aggregates	314,708
Of which	
Negotiated sales	31,840
Timber sales	2,065
Commercial, free-use, and community pits	259,880
Other	20,923
<b>Other minerals</b>	
Decorative stone	52
Clay (free-use and community pits)	2,925
Gold (in troy ounces)	219

<sup>1</sup> Excludes production for ODOT, county road departments, local governments, and commercial mining, which are included elsewhere in the survey.

### ACKNOWLEDGMENTS

The author thanks Bruce Weber, Department of Agricultural and Resource Economics, and Stanley Miles, Economic Information Office, both at Oregon State University, for helpful reviews of this paper. □

### DOGAMI honors volunteers at dinner

The Oregon Department of Geology and Mineral Industries (DOGAMI) has an active volunteer program. During the last year, 14 volunteers have donated 2,110 hours, or 263.75 working days, to DOGAMI. To show its appreciation, DOGAMI honored its volunteers at a dinner in Portland on November 30, 1994. Eleven of the volunteers who were present were given certificates of appreciation by State Geologist Donald Hull. Four of the volunteers, Wally McClung, Rosemary Kenney, Archie Strong, and Margaret Steere, who have donated more than 500 hours of volunteer service over the years to DOGAMI, also received engraved clocks.

Speaker for the evening was Robert Whelan, Minerals Economist for DOGAMI. He talked about the place of minerals in Oregon's economy, describing his work with DOGAMI and presenting some of the results of his recent survey of mineral producers in the state.

DOGAMI has had an active volunteer program since 1990. The two original volunteers, Margaret Steere and Rosemary Kenney, are still active in the program and were among the four given clocks for having donated more than 500 hours. Volunteers work primarily in the Nature of the Northwest Information Center or in the DOGAMI library but have contributed in other ways such as helping with field projects, office work, or mailings. New volunteers are always welcome, particularly in these days of dwindling budgets and heavier DOGAMI responsibilities, so anyone who would like to help is urged to contact Beverly Vogt, Volunteer Coordinator (phone 503-731-4100). □

# Episodic flooding of prehistoric settlements at the mouth of the Coquille River

by Roberta L. Hall, Department of Anthropology, Oregon State University, Corvallis, Oregon 97331, and Stefan Radosevich, Department of Anthropology, University of Oregon, Eugene, Oregon 97401

The archaeological record left behind by people who lived near the mouth of the Coquille River as long as 3,000 years ago provides evidence of past geologic events (Figure 1). The site chosen by Euro-American settlers for the initial commercial district of Bandon has proved through several archaeological investigations in recent years to have been intensively occupied in previous times by Native Americans who relied on the bounty of the forests, river, and ocean. The stratigraphy of the site also reveals interruptions in the human occupation, presumably signifying periods when the population had moved elsewhere, perhaps because the place became temporarily inhospitable. Besides these evident gaps, our investigation has also found evidence of human habitation at levels below the current water table and near the present sea level. These data suggest that significant changes in land and water relationships occurred due to sea level fluctuation, subsidence, uplift, or a combination of factors.

Site 35CS43 (35 designates the State of Oregon, CS designates Coos County, and 43 indicates that this was the 43rd site recorded in the county) on the Coquille River estuary is shown in Figure 2. Test excavations in 1988 (Hall and others, 1990) and in 1990 revealed thick layers of sand covering some of the occupation layers, which are rich in stone tools, shells, and bone fragments from fish, birds, and land and sea mammals. In one of eight 2-m by 2-m excavation units studied in 1990, two very large bowl-shaped objects made of unfired clay were uncovered from a depth of more than 1 m. Charcoal from a nearby unit of equivalent depth gave an estimated radiocarbon age of  $1,890 \pm 170$  years B.P. (Beta-41017). Preservation of the clay vessels is surprising—although their walls are several centimeters thick, the unfired vessels were not portable and would have been subject to breakage if left without protection for a length of time. Their preservation led us to postulate that the sand layer more than 30 cm thick that covered them had been deposited rapidly and had preserved the structure of the vessels (Hall, 1994).

Studies of geology and archaeology along the Pacific Coast have suggested that periodic earthquakes could produce such a deposit by inducing a tsunami or by causing rapid subsidence and the deposition of river-borne sediment (Atwater, 1987; Yeats, 1989; Darienzo and Peterson, 1990; Woodward and others, 1990; Komar and others, 1991; Nelson and Personius, 1991; Clarke and Carver, 1992; Komar, 1992; Nelson, 1992b). Evidence in the Coquille estuary of abrupt subsidence within the past 500 years that is believed to be related to earthquakes comes from analysis of buried peat in the Bandon marsh (Nelson, 1992a). Surveys of the head of tidewater over the past 150 years indicate that uplift is currently occurring in the lower Coquille basin (Benner, 1991).

Because of historic disturbance at Site 35CS43 at Bandon, information about very recent geologic events has not been found, but the site tells a long story of repeated flood and human occupation cycles over the past several thousand years. The resolution of whether the flood episodes that are evident at the archaeological site are episodes of tsunamis or of subsidence that are earthquake related could be advanced by geologic studies in the estuary and at other sites on the Pacific Coast, but studies at the Strait of Juan de Fuca (Mathewes and Clague, 1994) have shown that uplift and subsidence effects can vary greatly at nearby sites. Alternative hypotheses that could account for the strata of water-deposited sediment and the thick layers of sand include ocean storms, river floods, and dune movement.

To obtain additional data with which to explore these possibili-

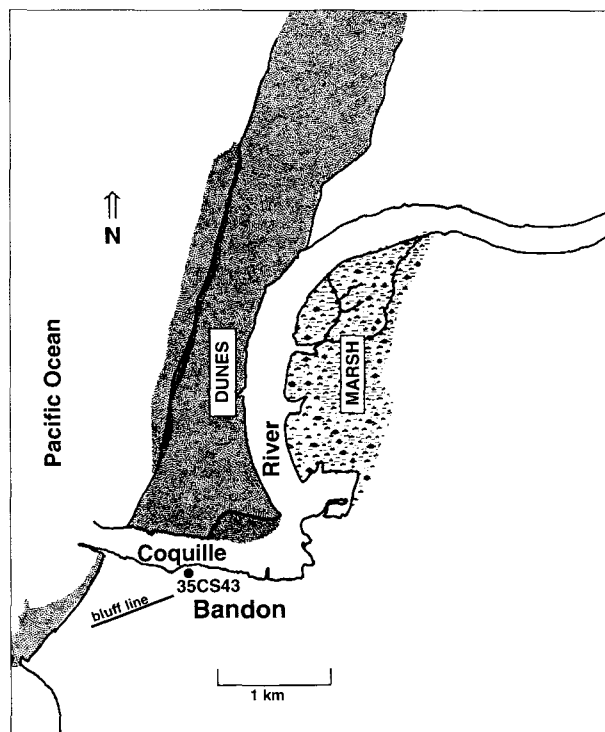


Figure 1. Map showing location of study area, Site 35CS43, on the Coquille estuary.

ties, a field project to remove cores from the site for detailed analysis of the stratigraphy and soils was carried out in August 1993. In addition, Unit 17, one of eight 2-m by 2-m excavation units studied in 1990, was reopened, and its north wall was stratigraphically analyzed. Figure 3 shows the location of the excavation units and the cores; Figure 4 shows the stratigraphy of Unit 17. A Giddings probe (Figure 5) was used to obtain the five cores. Samples from the cores and from the north wall of Unit 17 were tested for a battery of chemical elements and properties, most importantly for phosphorus, carbon (through loss on ignition), strontium, barium, calcium, and soil pH. In addition, mineralogic and grain size analyses were performed, and four radiocarbon tests were made.

Because the site was the location of Bandon's first commercial district, the upper 50 cm is disturbed; this has essentially removed stratigraphic information about the past 1,000 years. Below 50 cm, however, many pristine patches of deposits exist. All five cores gave indication of changes over time in the degree and intensity of human occupation and indicate variation in the topography, stratigraphy, and probably also in land and water relationships. Extending almost 3 m below the surface, cores went below the current water table and near the level of high tide at the river's edge. Cores 4 and 5 contained beds several centimeters thick that include relict bedding planes (Figure 6) giving visual evidence of past floodwater deposits. These deposits became the parent material of the resulting Inceptisols that constitute the site.

The beds in Cores 4 and 5 do not represent the same flood event, however. Considering all depths relative to the a single datum, the relict bedding plane in Core 5 lies 70 cm deeper than that in Core 4. In both cores, thick strata of shell-midden deposits occur below as well as above the flood deposit strata. Radiocarbon dates made from bulk soil samples of core several centimeters above each of the bedding planes confirmed their separation in time. The deeper sample from Core 5 produced a radiocarbon age of  $3,550 \pm 90$  years B.P. (Beta-69464), whereas the sample from Core 4 produced a radiocarbon date of  $1,250 \pm 60$  years B.P. (Beta-69462).

The 29 samples analyzed by Chemex Labs, Inc., of Sparks, Nevada, confirmed that soil formation processes at the site have included intense anthropogenic episodes separated by periods lacking human occupation. Strata that contained degraded midden deposits of invertebrates and vertebrates were very high in phosphorus (in several samples greater than 10,000 parts per million) as well as carbon, calcium, and strontium; pH was neutral to slightly alkaline (7.0-7.5). In contrast, two samples taken from soil on the bluff above the site and one sample from a previously excavated site on the estuary that does not contain midden deposits (Hall and others, 1992) were somewhat acidic (5.0-6.0) and relatively low in phosphorus, strontium, and calcium, but high in carbon (Table 1). Samples from parts of the cores that were not middens were low in phosphorus, strontium, calcium, and carbon, but were similar to midden samples in pH. The most intensely anthropogenic strata had a much greater concentration of phosphorus and carbon than archaeological sites in other areas that have been tested (Eidt, 1977; Moss, 1984; McDow-

ell, 1988, 1989; McDowell and Willson, 1991). Chemical tests thus confirm the episodic nature of human occupation at 35CS43 and tell a story of repeated occupation episodes, apparently separated by overbank depositions from floods.

In addition to radiocarbon tests on bulk soil in two cores, charcoal from level K from the north wall of Unit 17 (Figure 4) yielded a radiocarbon age of  $1620 \pm 60$  years B.P. (Beta-67695). Shell fragments also from level K yielded a radiocarbon age of  $2,270 \pm 60$  years B.P., which was reduced to  $1,880 \pm 70$  years B.P. after a standard adjustment was made to correct for upwelling that affects marine organisms (Beta-69461). These two estimates are in line with previous dates obtained in Area B (Hall, 1994). The lone, very old date of 3,550 years (noted previously) from a depth of over 2 m in Core 5 on the north side of First Street needs corroboration but is potentially of great interest, particularly since it lies above a relict bed of flood deposits, which itself overlies a shell midden.

Samples were analyzed for mineralogy by Sam Boggs and Pete Condon of the University of Oregon Department of Geology. Thin sections of soil samples from two of the cores and from depths of 70 to 168 cm below the surface at the north wall of Unit 17 were subjected to point-count analysis. After the fine-grained matrix that surrounded the clasts was removed, single quartz grains predominated, representing from 33 to 40 percent of the samples. Two other categories of quartz grains, polycrystalline quartz with abundant clay or iron oxide and coarse polycrystalline quartz with two or more crystals per grain, represented an additional 17 to 30 percent of each sample. Condon reported that the heterolithic nature and high grain



Figure 2. View from the bluff south of Site 35CS43, showing archaeological excavations conducted in the summer of 1990. This site was occupied by Native Americans periodically over the last several thousand years; it also was the location of the Coquille Ferry, which began operations in 1853, and was the site of the first commercial district of Bandon, which was developed in the late 1880s.

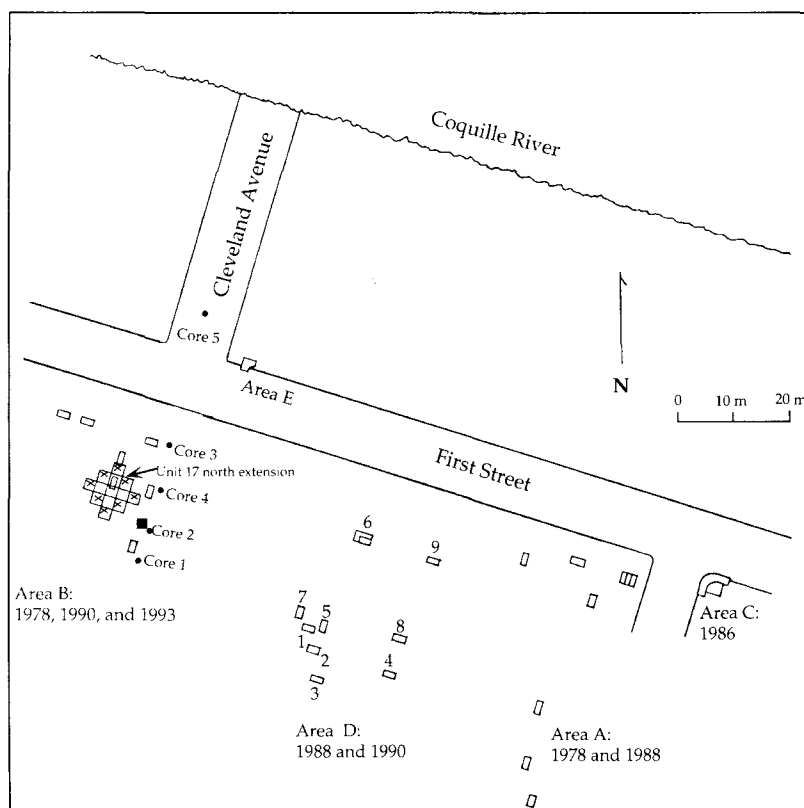


Figure 3. Map of excavation units and cores at Site 35CS43. This report draws on samples taken in August 1993 from the five cores and the north wall of Unit 17.

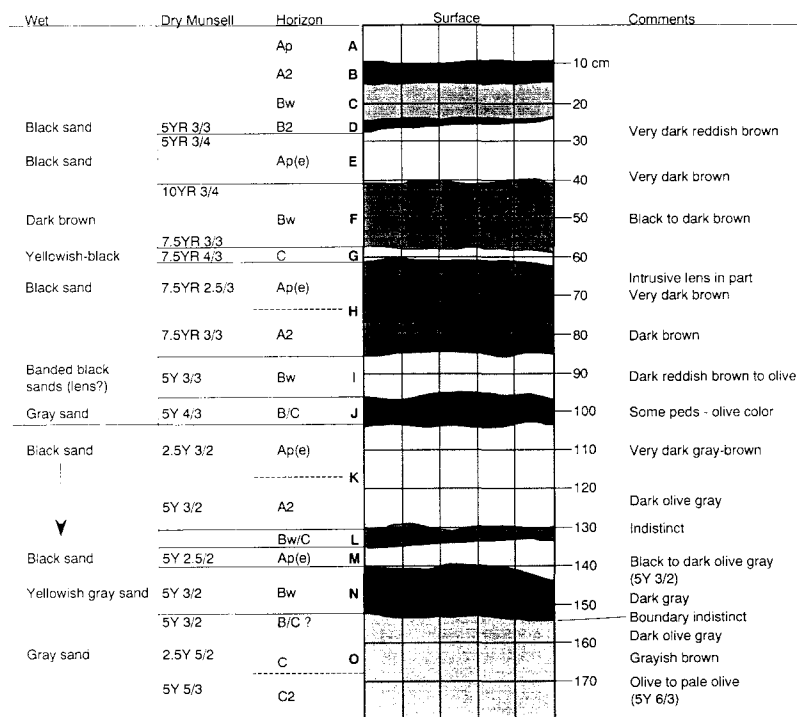


Figure 4. Schematic drawing of strata of the north wall of Unit 17. Color classifications are based on Munsell Soil Color Charts (Macbeth, 1990).

angularity of the samples suggests that they are immature, probably derived from erosion of several types of rock, and were not transported a great distance. Boggs and Condon concluded that the materials represent fluvial overbank sediments deposited at times of high water.

Grain-size analysis performed by Chemex Labs, Inc., indicated a bimodal distribution and great uniformity in all samples. The predominant fraction of 50 percent or more was of coarse sand to pebble sized clasts, while another sizable fraction of about 35 percent was of medium to fine sand, with little material falling between these extremes. Both the mineralogic and the grain-size analyses showed that site samples differed greatly from the soil samples taken from the bluff above the site and gave several indications of a riverine origin. The implication is that the parent materials for the site lie not far upriver in the Coquille River basin. Determining the cause of the overbank deposits requires further inference, however. A historic flood such as was observed in 1861 (Komar and others, 1991, p. 15) could move deposits downriver, or an ocean storm could move into the estuary and upriver, where it could pick up sediments for deposition near the mouth. Similarly, a tsunami set off by a subduction-zone earthquake would be expected to produce a great surge of water that could move up the estuary, pick up sediment from upriver, and deposit it near the mouth on its return.

Radiocarbon tests provide a basic framework for understanding archaeological or geologic events but not a precise history, because they define a range of years rather than an exact date (Nelson, 1992a). Ideally, it would be useful to determine whether the flood events recorded in our cores are correlated with evidence of subsidence or floods elsewhere in the estuary or along the southern Oregon coast. Data from Bradley Lake, 5 km south of the Coquille estuary, suggest three earthquake subsidence episodes at approximately 300, 1,000 and 1,600 years ago (Nelson and others, 1994). Because our date from Core 4 is based on bulk material above the flood deposit bed, we infer that the flood recorded in Core 4 occurred before 1,250 years ago and thus could refer to the subsidence event of 1,600 years ago at Bradley Lake. The flood deposit evident in Core 5 precedes recorded subsidence events and offers lines of study for geologists in nearby areas. While these results are suggestive, they are far from conclusive. To establish the contemporaneity of geologic events, more radiocarbon dates would be required both above and below the flood-deposition strata. Thus, while we have made a case for the existence, over the past several thousand years, of a series of changes in land and water relationships at the mouth of the Coquille River, we have not been able to select or eliminate any of the hypotheses that singly or together could account for the episodes.

Multiple forces working at the river's mouth have made the geological and archaeological records difficult to interpret. Natural factors that make the site complex include the Coquille River, which has been known to flood in historic time; the

presence of a bluff to the south of the site that stands about 25 m above sea level and includes 100,000-year-old marine terraces; a creek that flows down the bluff to the west of the site but in early historic time probably passed near or through the site and could have caused erosion; dune movement and changes in the river's course and the position of its mouth; processes of subsidence and uplift that could have been sudden or gradual; ocean storms that may have surged up the estuary and onto the site; and tsunamis that may have been generated by earthquakes. In addition, human activities have contributed to the complexity of the site. Upper levels have been disturbed by the construction of footings and basements for buildings, laying of water and sewer lines, and two devastating fires that swept Bandon in 1914 and 1936 and resulted in deposition of large amounts of debris. The effect of early native communities is evident below the debris left by settlers in historic time. At the time of contact

with Europeans, native homes were dug as much as a meter into the ground, and this practice likely dates back into prehistoric time as well. In addition to construction activities, the natives' extensive food-gathering and food-preparation activities changed soil characteristics. Shellfish middens built up the soil and also raised the pH, retarding decomposition of animal bone refuse.

Greater specificity in dates from site 35CS43 and from buried tidal-wetland soils along the coast may help to resolve historic questions regarding the cycles of human settlement and geologic questions regarding the incidence and effects of floods and earthquakes. Whatever the causes for the periodicity of settlement and floods, the prehistoric data are consistent with other studies of coastal margins, which indicates the need for caution in coastal and river-front development in Bandon and other towns of Oregon's Pacific coast (Komar, 1992). While development of the Bandon

Table 1. *Phosphorus, pH, loss on ignition, strontium, and calcium in selected samples*

Samples	Phosphorus (P) (ppm)	pH	Loss on ignition (percent)	Strontium (Sr) (ppm)	Calcium (Ca) (percent)
Midden in Unit 17, level K	>10,000	7.5	7.0	467	6.43
Near bed in Core 4	690	7.7	2.6	187	1.22
Bluff, 50 cm	350	5.2	5.8	162	0.61
Ferry Creek site <sup>1</sup>	520	5.2	9.6	132	0.74

<sup>1</sup> Sample from excavated trench at Ferry Creek waste-water treatment site, 1 km upriver from 35CS43, which on investigation proved not to be a prehistoric human settlement (Hall and others, 1992).



Figure 5. Stefan Radosevich and Roberta Hall watch as David Liberty uses the Giddings probe to remove a core for soil analysis in the field project at Site 35CS43 in August 1993.



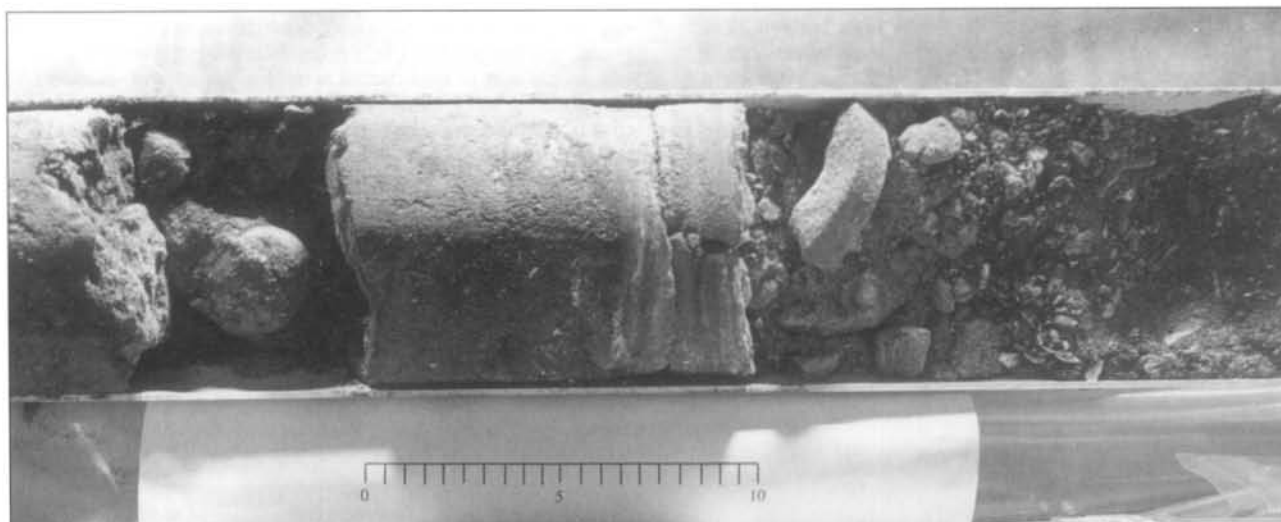


Figure 6. Portion of Core 5 containing distinct bedding plane. Note shell midden below it (to the right in the picture).

jetty 100 years ago (Hall, 1992) has stabilized the mouth of the river in the short run, it may not protect the coastal area from major hazards. Archaeological data indicate that prehistoric people also had a major impact on the lands they occupied, but, like contemporary societies, their continuation ultimately depended upon natural forces. Data from geology and archaeology together provide insights into the struggles and solutions of people in the past and should be used to anticipate and prepare for geologic forces in the future (Yeats, 1989).

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