4. Tsunami Deposits

Tsunamis flooding Seaside have left behind distinctive sheets of sand (hereafter referred to as tsunami deposits) that can be interpreted to reconstruct the history of tsunamis. These tsunami deposits are similar in appearance to those found by other researchers studying tsunamis along the Cascadia margin (Peters *et al.*, 2003). The spatial distribution of tsunami deposits in Seaside is hard evidence of tsunamis that establishes minimum inundation areas (Jaffe and Gelfenbaum, 2002). Tsunami deposit age, combined with this spatial distribution, can be used to estimate the relative magnitude of near- and far-field tsunamis and to determine the frequency and magnitude of tsunami inundation.

The value of incorporating a tsunami deposit component in probabilistic tsunami hazard assessments is underscored by the fact that the only record of tsunamis generated by earthquakes on the Cascadia Subduction Zone impacting Seaside are from tsunami deposits. Tsunami deposits verify the ability of the Cascadia Subduction Zone to generate large tsunamis that impacted Seaside in the past. Tsunami deposits define the lower limit of the inland extent of inundation. In this study, we have not interpolated between these point measurements, although in some locations it would be justified because they are close together. The spatial distribution and ages of tsunami deposits were used in this study for validation of the hydrodynamic model runs. The focus of tsunami deposit validation for modeling was on two events—the near-field 1700 Cascadia tsunami and the far-field 1964 Alaska tsunami.

Tsunami deposits also are tangible evidence of tsunamis in Seaside that the public is able to relate to. Locations of known tsunami deposits overlain on an inundation map, or, for this study, on a map showing the 100- and 500-year tsunami flooding lines, validate study results for the public, emergency planners, and managers. Digging a hole and seeing a tsunami deposit makes believers out of even the most skeptical—a tsunami flooded this location.

This study benefited from extensive research on tsunami deposits in Seaside conducted by Curt Peterson and his students in the 1990s (Darienzo and Peterson, 1995; Darienzo *et al.*, 1994; Fiedorowicz, 1997; Fiedorowicz and Peterson, 2002; Peterson, 1993). It is possible to generate a tsunami deposit record for use in a probabilistic tsunami hazard assessment without previous studies. When the geometry of the site is simple, there is less need for preexisting tsunami deposit data. In the case of Seaside, which has a complex geometry (two shore-parallel rivers bounded by high beach ridges), without preexisting data the tsunami deposit component of this study would require additional effort and would not have produced as complete a record of past tsunamis.

4.1 Methods

The methods used in the tsunami deposit component of this study are standard for the geologic tsunami research community. These methods can be transported to other sites where FEMA requires a probabilistic tsunami hazard study. It is essential that scientists performing a tsunami deposit study have experience identifying tsunami deposits and knowledge of geologic environments where tsunami deposits are likely to be formed and preserved. Without such experience and knowledge, the quality of a tsunami deposit study is compromised and the results of such a study are of limited usefulness.

We used a combination of preexisting sedimentary data and new sedimentary data collected specifically for this study to map out the distribution of past tsunami inundation in the Seaside area. We examined and re-evaluated logs of cores, trenches, and cut banks from previous work done in Seaside during 1996 by Brooke Fiedorowicz and Curt Peterson (Fiedorowicz, 1997; Fiedorowicz and Peterson, 2002). The existing data set, collected at 236 sites in the 1990s, was supplemented by additional fieldwork to increase the data density, provide data where existing data was not available or clear, and to extend the boundaries of the survey farther inland and farther to the south of Seaside. Cores, trenches, and cutbacks were examined and logged from 76 locations in the Seaside area during the summer and fall of 2004 (Fig. 6). Overall, data from 312 locations were included in the survey (Fig. 7).

In addition to sedimentary data, we used a database that contains 66 observations by Seaside, Oregon residents of inundation, runup, and water levels from the 1964 tsunami in Seaside, recorded by Tom Horning, and included in the master's thesis of Brooke Fiedorowicz (1997). Other locations of possible tsunami sand layers and tsunami mud layers based on these eyewitness observations were also noted and categorized as locations where the 1964 tsunami was known to have inundated. We included an additional five observations of areas with no sedimentary deposits that are presumed to have not been inundated by the 1964 tsunami.

The ages of the deposits were determined using a combination of radiocarbon dating, stratigraphic context and, for 1964 tsunami deposits, historical documentation. Correlations between deposits were based on stratigraphic context and lateral continuity between deposits. Tsunami deposits stratigraphically below the 1700 event were deposited by earlier tsunamis.

4.2 Results

Deposits from five tsunamis in the past 2000 years were found at 167 sites located as far as 2 km inland along the 5-km stretch of coast at Seaside. Deposits were found primarily in marshes fringing the Necanicum River and Neawanna Creek, which flow parallel to the coast between beach ridges that are 5 to 10 m high.

Tsunami deposits in the Seaside area usually occur as anomalous sand layers within mud or peat layers (Fig. 8). The following additional criteria were established for the Seaside area to determine whether a sand layer had

(a)

(b)

Figure 6: (a) Bob Peters and Curt Peterson coring at Stanley Lake; (b) Bruce Jaffe digs a trench while Curt Peterson cores along Neawanna Creek.

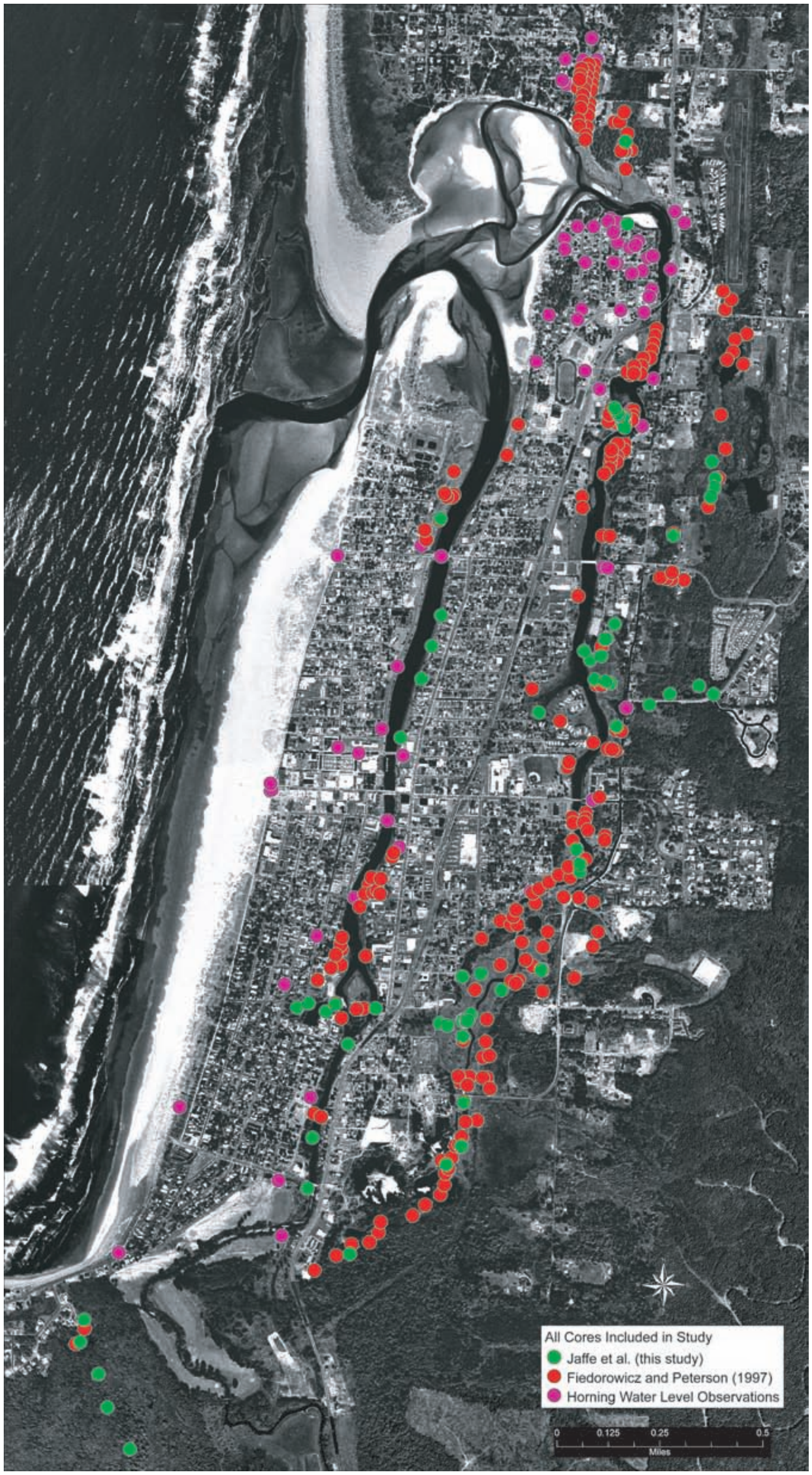

Figure 7: Locations of gouge core and trench sites visited by Tom Horning (1996), Fiedorowicz and Peterson (1997), and Jaffe *et al.* (2004).

(a)

(b)

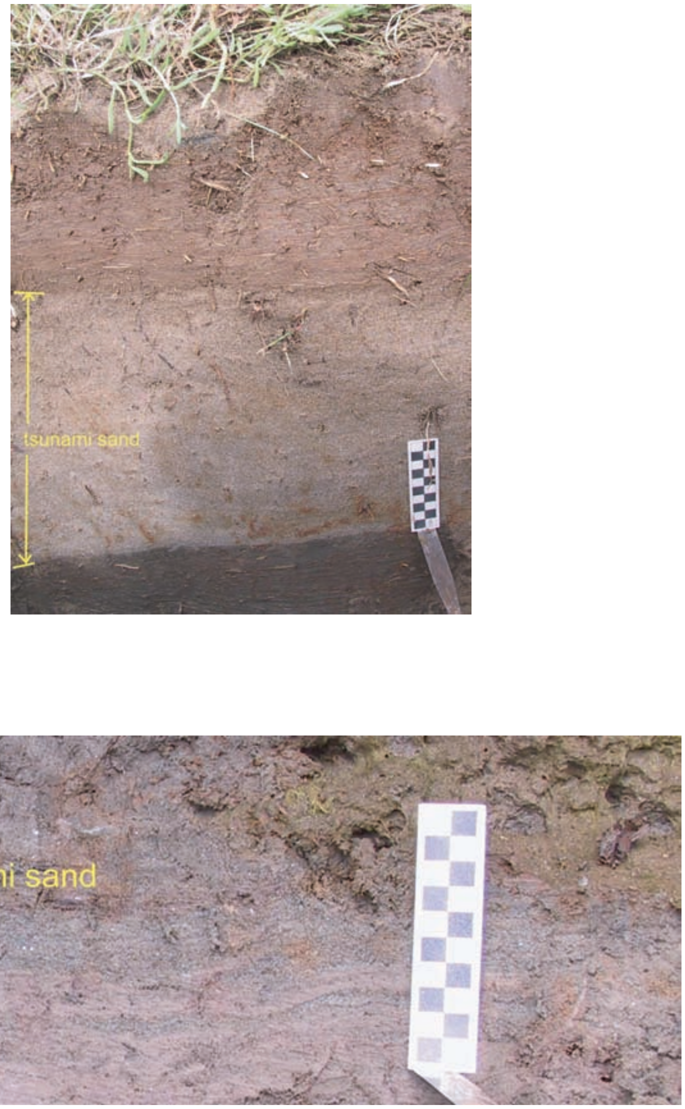

Figure 8: (a) Deposit from 1964 tsunami in Neawanna Creek trench; (b) Deposit from 1700 tsunami exposed in Neawanna Creek cutbank.

a tsunami origin: normal grading, presence of organic detritus, particularly as a detrital cap; a noticeable decrease in the amount of peat from the underlying material to the overlying material; lateral continuity; presence of rip-up clasts; presence of sand/mud couplets; and historical documentation. With the exception of historical documentation, no single criterion is wholly diagnostic. A combination of stratigraphic context and lateral context, combined with one or more of the identifying criteria, were used to assign a tsunami origin to a particular deposit. See Peters *et al.* (2003) for a discussion of tsunami identification criteria.

We focused on defining tsunami inundation from tsunami deposits for the 1964 far-field and 1700 near-field tsunamis to develop a dataset for validating hydrodynamic models.

4.2.1 1964 tsunami deposits

Tsunami deposits from the 1964 tsunami were identified at 116 sites (Fig. 9; Appendix D). Tsunami deposits from the 1964 Alaskan tsunami were typically found within a few tens of centimeters of the surface. In contrast, tsunami deposits from the 1700 Cascadia tsunami were typically covered by more than 0.5 m of sediment. The stratigraphic features of the 1964 tsunami deposits are very different than those of a storm deposit (Morton *et al.*, in press), allowing discrimination between the two types of deposits. Inundation during the 1964 tsunami was primarily up channels. Tsunami deposits were limited to the banks of channels, primarily the Necanicum River, Neawanna Creek, and Neacoxie Creek. Along Neacoxie Creek, deposits were found as far upstream as the G Street Bridge in Gearhart (Fig. 4c). Residents observed tsunami inundation over the bridge and beyond it. There was a log jam at the bridge and the water backed up behind the bridge. In Seaside, deposits from the 1964 tsunami are found along Neawanna Creek as far south as 16th Avenue. Residents observed the tsunami as far south as the 12th Avenue Bridge. Tsunami deposits from 1964 on the Necanicum River are found as far south as Avenue Q. Eyewitness observations indicate that the 1964 tsunami inundation reached the golf course south of Avenue U (Fig. 4c).

Tsunami deposits were found primarily within the inundation line determined from eye-witness reports (Appendix C, Figs. 4 and 9). The distribution of 1964 tsunami deposits was a close approximation of the area of inundation along the Necanicum River determined from historical observations, but significantly underestimated the area of inundation along Neawanna Creek.

4.2.2 1700 tsunami deposits

Deposits from the 1700 tsunami were present at 119 sites in the Seaside area (Fig. 10; Appendix D). The 1700 tsunami deposit is usually found approximately 0.5–1 m below the surface and in many places forms sand sheets that are laterally continuous for tens to hundreds of meters. The sites available for investigation were limited to those not developed or otherwise disturbed since 1700. Long stretches of the banks of the Necanicum River and Neawanna Creek have been covered with fill so that residential or commercial structures could be built or to create pasture land. Armoring of the banks also made many areas possibly inundated by the 1700 tsunami inaccessible for coring or trenching.

Deposits from the 1700 tsunami east of Neawanna Creek were found at Stanley Lake and along Shore Terrace Road as far east as the trailer park. Fiedorowicz (1997) reconstructed the geography present during the 1700 tsunami by interpreting geologic deposits. The tsunami probably entered Stanley Lake through the outlet at the north end of the lake. The deposits along Shore Terrace Road are best explained by the tsunami overtopping the dune ridge that separates Neawanna Creek from the lowlands to the east. Deposits from the 1700 tsunami were found along the banks of the Necanicum River as far south as Avenue U and along the banks of Neawanna Creek in the reaches south of the millponds. In Gearhart, deposits from the 1700 tsunami were also found

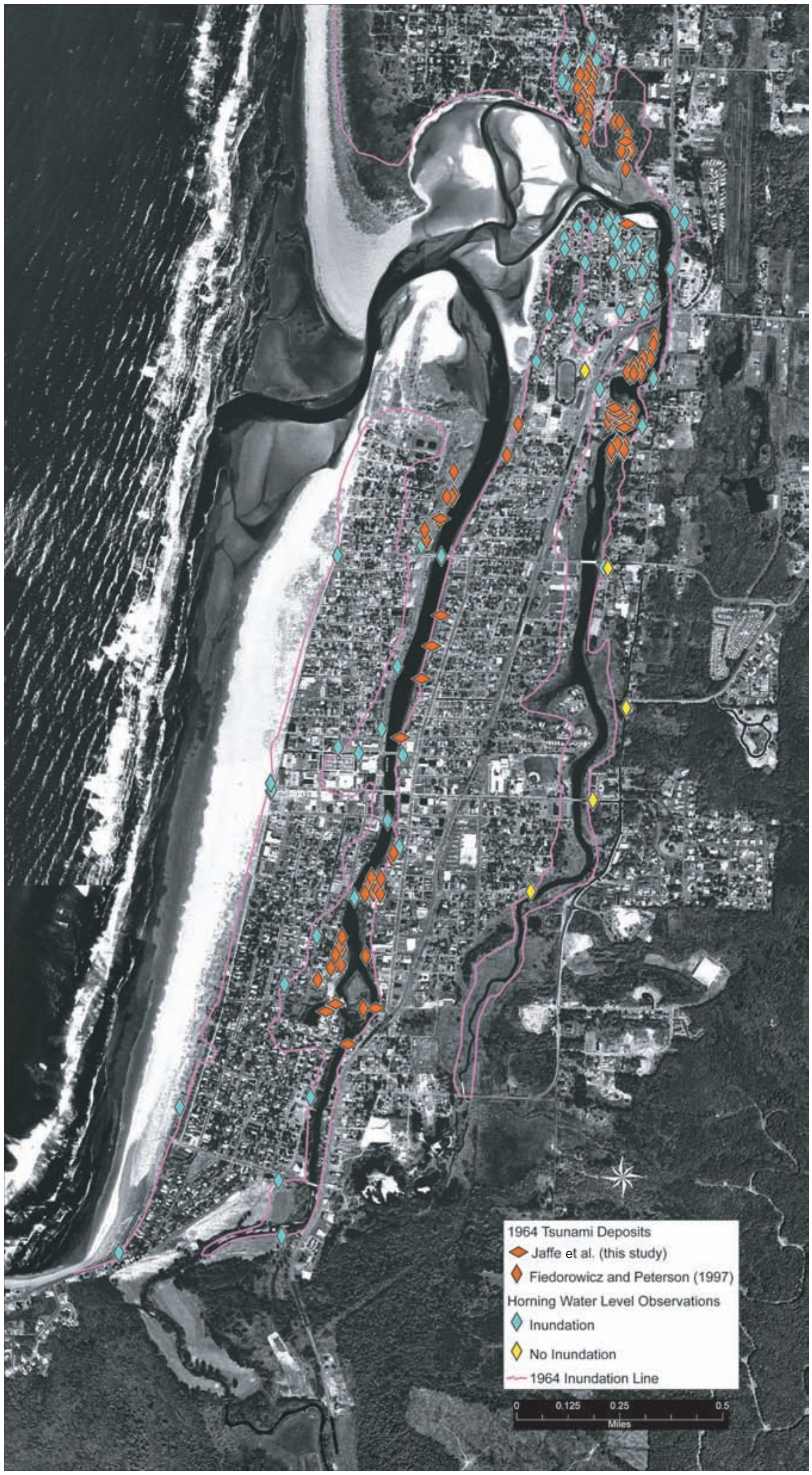

Figure 9: Sites containing 1964 tsunami deposits.

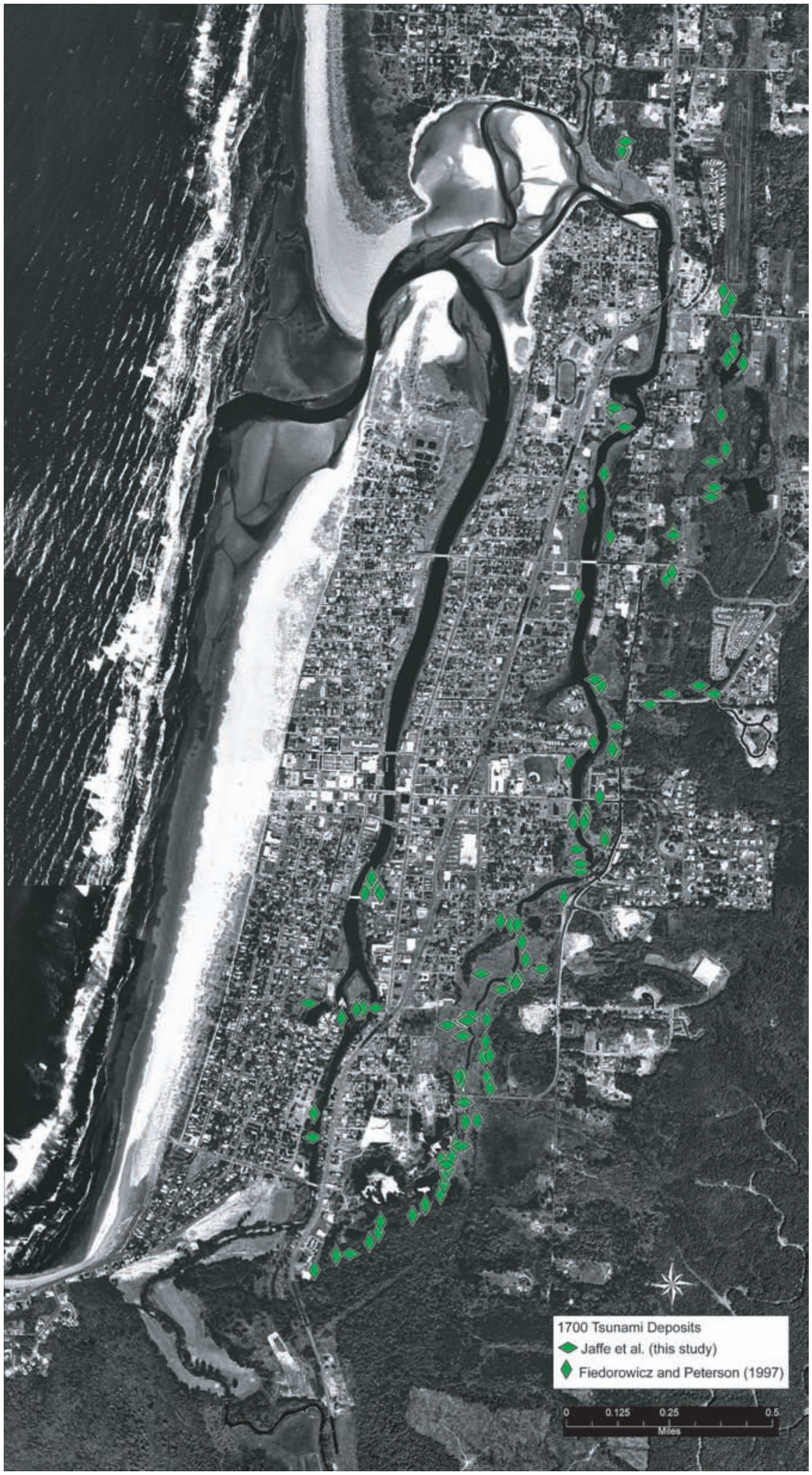

Figure 10: Sites containing 1700 tsunami deposits.

along the banks of the small creek east of the present Neacoxie Creek, but no deposits from the 1700 tsunami were found along Neacoxie Creek. Geological evidence suggests that Neacoxie Creek is younger than 1700 (Fiedorowicz and Peterson, 2002).

The 1700 tsunami may have overtopped the narrow gravel ridge between the Necanicum River and Neawanna Creek north of Avenue P. It may also have overtopped the considerably wider gravel ridge complex at 4th Avenue.

4.2.3 Older tsunami deposits

Deposits from tsunamis older than the 1700 tsunami are also found in the Seaside area (Fig. 11). Deposits from tsunamis older than the 1700 event were found at 36 sites. Of particular interest are deposits dated at 1230 ± 30 years B.P. and 2770 years B.P. that are located south of the bend in the Necanicum River south of Seaside. These radiocarbon dates are based on spruce cones found within the deposits. This area may have been a paleo-outlet for the Necanicum River. Deposits from events older than the 1700 event are also found along the banks of the southern portions of Neawanna Creek. In the vicinity of Avenue P, north of the Avenue S Bridge, a deposit from a tsunami that occurred prior to 1700 can be seen at low tide along the cut banks of Neawanna Creek. This deposit lies stratigraphically below the 1700 deposit. Deposits from tsunamis older than 1700 are also found in cores from the Stanley Lake region.

4.2.4 Paleo-tidal inlet

The distribution of the 1700 tsunami deposits and morphological features prompted us to hypothesize that the inlet was located further south than its present location when the 1700 tsunami impacted Seaside. A preliminary investigation using Ground Penetrating Radar (GPR) found a sediment-filled valley between the Necanicum River and the Pacific Ocean that could have been formed by an inlet approximately 1 to 1.5 km south of its present location.

North-south GPR lines collected along Downing Street and the full length of Front St. (north-south parallel to Necanicum River) detected the banks and the bottom of the paleo-inlet. Curt Peterson and David Percy (Portland State University) ran additional north-south GPR lines to confirm location of the paleo-inlet and west-east lines to check for channel fill versus beach progradation strata. At the southern portion of the sediment fill, north-dipping reflectors indicate a northward migration of the paleo-inlet. Change from northward-dipping reflectors to flat or landward-dipping reflectors occur at approximately 50 m south of A Street, marking the southern extent of the paleo-inlet. Paleo-tidal inlet depth was a maximum of 5 m below mean sea level. The inlet fill is approximately 1.3 km wide; the size of the paleo-inlet was less because the fill is created by migration or narrowing of the inlet. For comparison, the widest portion of the present inlet is approximately 0.7 km wide. The north side of the paleo-tidal inlet begins just south of 15th Street in Seaside (on Franklin S-N extension of Downing Street about 3 blocks south of the waste water treatment plant).

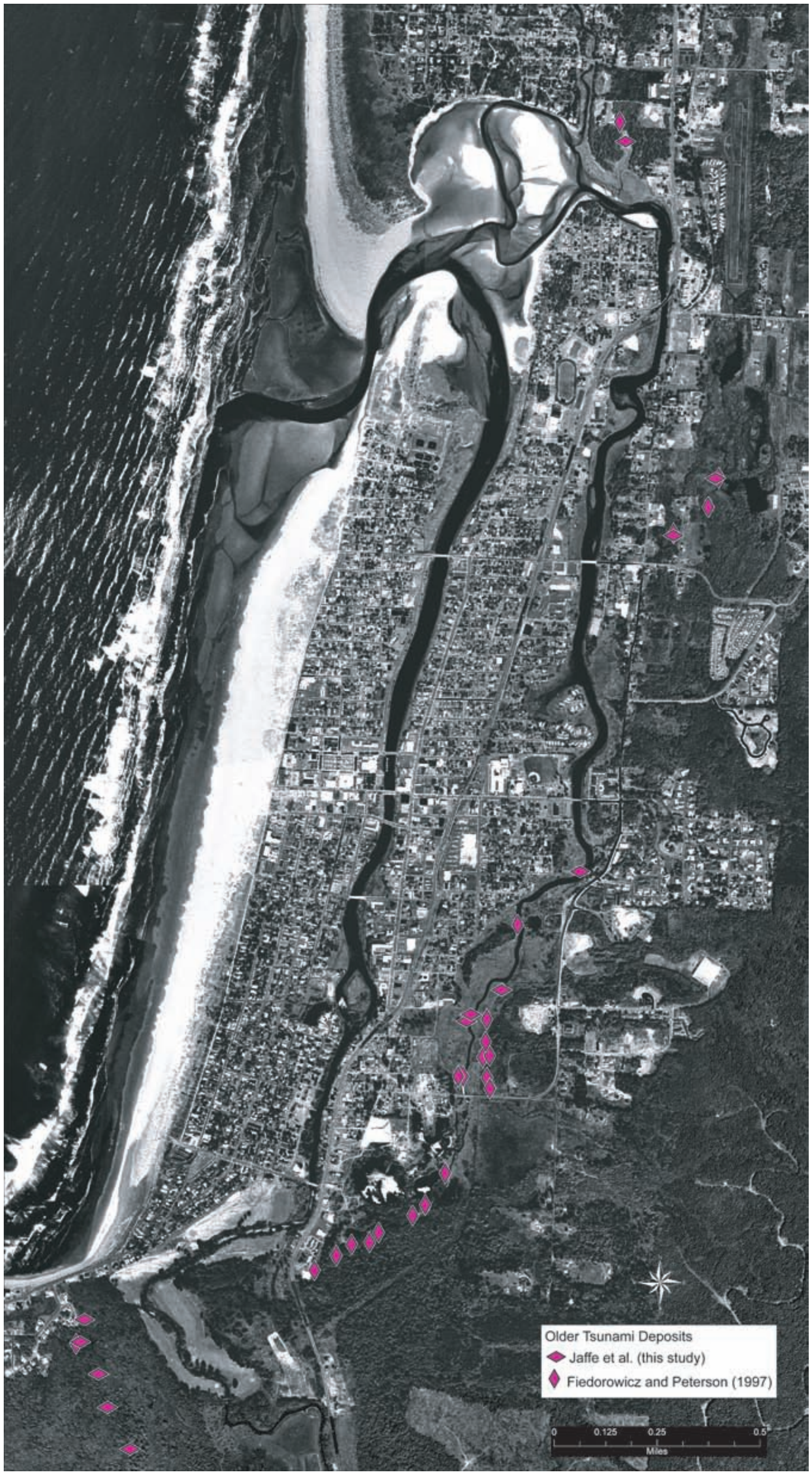

Figure 11: Locations of older tsunami deposits.

Reflectors imaged by GPR constrain the history of the inlet. At 1st Street, a progradational beach facies (seaward dipping reflectors) starts 50 m east of the present landward extent of the beach (the boardwalk), indicating that the closing off of the inlet and building out of the beach there is relatively recent. Moderately-deep reflectors dipped south (toward the paleo-inlet channel) at the northern end of the inlet fill, confirming that the channel "jumped" to its present position (north of the waste-water treatment plant) rather than by a gradual migration north, which would have left north dipping reflectors. The jump may have occurred immediately after the catastrophic flooding by the 1700 AD tsunami event.

4.3 Discussion of Tsunami Deposit Results

The tsunami deposit record for Seaside establishes that near-field tsunamis generated by great Cascadia Subduction Zone earthquakes are significantly larger than the 1964 far-field Alaska tsunami. Deposits from the 1700 tsunami are found up to 2 km inland near the base of the hills on the east side of town (Fig. 10). The spatial distribution and characteristics of 1700 tsunami deposits indicates that the 1700 tsunami overtopped the ridge east of Neawanna Creek—the 1700 tsunami was large even this great distance inland. Geological and archeological evidence indicates that this and other high gravel ridges have been present in Seaside for many centuries (Fiedorowicz, 1997). In contrast to the extensive spatial distribution of 1700 tsunami deposits, deposits from the 1964 tsunami are confined to the margins of Neawanna Creek and the Necanicum River—indicating a smaller tsunami that was not able to overtop the high gravel ridges at Seaside. Geological and archeological evidence indicates that this and other high gravel ridges have been present in Seaside for many centuries (Fiedorowicz, 1997). In contrast to the extensive spatial distribution of 1700 tsunami deposits, deposits from the 1964 tsunami are confined to the margins of Neawanna Creek and the Necanicum River—indicating a smaller tsunami that was not able to overtop the high gravel ridges at Seaside. The presence of tsunami deposits older than 1700 far inland is evidence that the 1700 tsunami is not an outlier in terms of size. The Seaside area has been inundated by large tsunamis many times in the past.

The inundation zones derived from the tsunami deposit data in this report are minimums because of limitations inherent in deriving inundation from tsunami deposits and limitations in the scope of this study. Where there is a suitable environment for deposition and preservation of tsunami deposits, data from modern tsunamis (Gelfenbaum and Jaffe, 2003; Jaffe *et al.*, 2003) indicate that the inland extent of tsunami deposits and of flooding are usually within 50 m—using tsunami deposits as proxy for limit of inundation does not introduce significant error. However, inundation extent is underestimated if a deposit never formed because there was not a source of sediment. A larger source of error in mapping inundation using only tsunami deposits, especially for tsunamis that occurred hundreds or thousands of years ago, is erosion of tsunami deposits. Preservation potential must be carefully evaluated in a probabilistic analysis of inundation and used as a filter for evaluating tsunami deposit data. Although a large number of sites (312) have been examined in Seaside for tsunami deposits, it is probable that further investigations will increase the estimate of the area of inundation, especially for older tsunamis.

Changes in topography or bathymetry need to be accounted for in using tsunami deposits to estimate the magnitude of past tsunamis. For Seaside, inlet location is a primary control on tsunami inundation. Deposits from the 1964 tsunami extended farthest inland at the inlet, indicating that it served as a conduit for the tsunami. Preliminary investigations using Ground Penetrating Radar (GPR) found a sediment-filled valley that could have been formed by an inlet to the south of its present location. If this inlet was open when the 1700 tsunami impacted Seaside, tsunami deposits could be expected to extend farther directly inland of the inlet. Additional studies are needed to determine the time when it was open to the sea.

Shoreline stability must also be taken into account when using tsunami deposits in a probabilistic tsunami hazard study. Change in shoreline position was observed but not accounted for in the Pilot Study and does not introduce large errors into the analysis of the 1700 and 1964 tsunamis, but could for older tsunamis. Estimates of inundation from tsunami deposits at a site where there is an eroding (prograding) shoreline underestimates (overestimates) tsunami inundation. For tsunami deposits to be most useful for validation of hydrodynamic models, paleoshorelines, paleotopography, and paleobathymetry should be established.

Because of its geologic setting, complex topography, and inlet migration history, Seaside is not a good location to develop tsunami recurrence intervals. Sites with simple topography and a coastal geologic setting that favors deposition and preservation of tsunami deposits are best used for developing tsunami recurrence intervals. Tsunami recurrence intervals have been established for Cannon Beach (Peterson *et al.*, 2004), which is 13 km south of Seaside. If a site-specific tsunami recurrence interval based on deposits were required for this study, it could have been developed using a combination of the Cannon Beach and Seaside tsunami deposit records. Use of tsunami deposit records from nearby locations is acceptable for developing tsunami recurrence intervals in a probabilistic tsunami hazard study.

Even with the complexities encountered in the study of tsunami deposits at Seaside, we were able to develop a robust tsunami record using standard geologic tsunami research methods. This record established minimum inundation zones from past tsunamis and was the only data available for validation of near-field tsunamis generated during Cascadia Subduction Zone earthquakes. An additional benefit of a tsunami deposit component to this study is that tsunami deposits were useful as an educational tool for the general public, emergency planners, and managers.